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Nondestructive Evaluation

A Report of the

NMAB NATIONAL MATERIALS ADVISORY BOARD

NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES-NATIONAL ACADEMY OF ENGINEERING

NONDESTRUCTIVE EVALUATICN

Prepared by

The Ad Hoc Committee on Nondestructive Evaluation

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NOTE

This publication is made up of the correlated report of the main Committee and of the special reports of its five panels, as follows:

The subject of Specifications and Standards, which is an important factor in the over-all consideration of nondestructive evaluation, is being dealt with in a separate supplementary report.

These sections have been paged separately, each with its own table of contents, and have been set apart by colored divider sheets.

PREFACE

The past two decades, particularly, have seen what has been popularly described as the "materials explosion," a burgeoning not only of improved materials of construction, but new concepts for materials (dispersion strengthening, composite reinforcement, cermets and ceramics, pyrolytic graphite, sandwiches, etc.), accompanied by improved and novel fabrication and joining techniques. The simultaneous increased complexity of equipment and vehicle systems to meet the ever-demanding requirements of defense and space exploration has forced designers to attempt to exploit these new materials and techniques with greater sophistication and efficiency in their design approaches. In so doing, the designers have availed themselves of every possible technical contribution: new design concepts, materials at maximum strength with minimum flaws, the understanding of crack initiation and propagation, etc. Understandably, the ultimate users, desiring the best of all worlds, have compounded the problems by adding to their exacting functional and design requirements more stringent reliability constraints, to assure safety of personnel and mission.

Inherent in the above scheme of development and optimization must be assurance, at every stage, of rigorous attainment of the pre-established quality upon which the design has been based with minimum safety factors to maximize design efficiency. It is obvious also that as the criticality of application has increased, the trend toward requiring 100% quality assurance has also increased, obviating the possibility of destructive testing (e.g., through sampling inspection) and, to a significant degree, the use of proof testing for both technical and economy reasons. Thus, the net result of designing with relatively new materials, concepts and fabrication techniques, combined with more exacting requirements and increased reliability, has been the growth of an urgent need for more effective and more comprehensive approaches for nondestructive testing and evaluation.

In the light of this situation which has, in fact, been recognized in a general way in many quarters, it is rather anomalous that there has not been a determination of the necessary elements of an adequate, nondestructive evaluation (NDE) system. These elements are both administrative and technical, comprising as they do the gamut from contract planning and definition through the introduction of novel NDE techniques by adaptation of new concepts from other disciplines, such as physics and chemistry. The request from the Department of Defense in 1967 for a broad study was most timely, therefore, and was received very enthusiastically by the NDE community, which had long sought such an opportunity.

The Committee which conducted the study reported herein took a broad view of the subject. It looked back over the years at the history of NDE, at the long-standing problems (20% of which, they concluded, still remain essentially unchanged after a decade or more), at some unfortunate national, serious failures which have occurred and which, in good likelihood, might have been averted had an adequate NDE system been available. It studied not only the salient defense inspection problems requiring technical definition and solution but also contractor problems in dealing with them, the specification problem, the need for recognition of NDE as an essential dimension in early system planning, the requirements for training technicians and engineers to insure the availability of a knowledgeable cadre from which Government and industry could draw for planning and program implementation. In a special session, the Committee provided a forum at which some forty scientists and engineers, from many sources and disciplines, came together to freely exchange ideas and to stimulate innovative and wider interest in NDE. From this emerged an early advisory report to DOD pertinent to initiating a broad research program. Those attending this forum enthusiastically urged a repeat performance after approximately a year. Some of the thoughts of the Committee have served as a partial basis for establishing the Research Division within the Technical Council of the American Society for Nondestructive Testing.

It is clear that NDE is an important factor in many areas: in design-materials planning, in fracture prevention, in the introduction of new materials and fabrication concepts, in general quality assurance, in performance monitoring, etc. It is hoped that this report will prove useful, in addition to benefits from its specific recommendations, in focusing attention in proper national sectors on the multi-faceted aspects of this broad and important subject.

N. E. Promisel

Washington, D.C.
December 1, 1968

SECTION I

Report

Of

The Ad Hoc Committee on Nondestructive Evaluation

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Professor L. M. Epstein	- "Applications of Mössbauer Effect"
Professor Hans Frauenfelder	- "Radiation"
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SECTION I

REPORT OF THE *AD HOC* COMMITTEE ON NONDESTRUCTIVE EVALUATION

CONTENTS

ABSTRACT

Recommendations are made to DOD which would enhance the greater utilization of the potentials of nondestructive evaluation (NDE) for present and future military systems. An integrated plan is presented which takes into account short- and long-range technical problems, lack of professional manpower, educational requirements, specification deficiencies, and requirements for basic research. Current NDE problems of military, indeed national, importance and scope are delineated, and approaches for potential solutions are outlined.

I. SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

If materials are to be designed to their limits to satisfy the ever-increasing demands of sophisticated military, aerospace, and industrial systems, it is necessary that nondestructive evaluation be deliberately considered for incorporation into every phase of the design-production-service cycle. This is specially important in the screening and qualification of candidate materials to meet new design criteria and in monitoring production processes and service life. The Committee believes that, even in the presence of adequate technology, the key to NDE implementation is the proper application of specifications.

The term nondestructive evaluation (NDE) is considered more appropriate than nondestructive testing and inspection (NDT&I) and will be used herein since:

(1) this discipline also requires the evaluation of test results and inspection;

(2) the words "testing and inspection" do not properly imply the theoretical aspects of this field; and

(3) the name is more succinct and descriptive.

The Committee recommends the following basic plan to DOD:

1. Require more effective utilization and development of NDE by suitable procurement specifications.

2. Encourage and assist the supply of trained NDE personnel from academic institutions through the demand created by proper specifications and by funding appropriate undergraduate and graduate programs.

3. Minimize repetitive development activities by further implementation of the existing NDE Information Analysis Center.

4. Establish DOD Centers-of-Excellence in NDE, devoted to the R&D necessary for the solution of national problems.

5. Initiate a long-range interdisciplinary research program to insure that all possible energy-material interaction phenomena are recognized for their potential to NDE.

The items in this plan are discussed in greater detail in the recommendations below and, particularly, in the sections which follow.

1. Education and Promotion

An alarmingly small number of professionals are available to provide a cadre for the multidiscipline approach necessary to meet the objectives of increased design criteria and safety.

Recommendations:

a. Encourage the implementation of appropriate graduate and undergraduate programs in NDE by making universities aware of DOD's needs through supporting contracts.

b. Establish national NDE research and application centers.

2. Information

The need for information dissemination is particularly acute in NDE since many different disciplines are involved. Monthly acquisition lists of current literature, including abstracts, are acutely needed to make new developments quickly available to those engaged in research, development, production, and field service of materials and products.

Recommendation:

a. Expand the activities of the DOD Nondestructive Testing Information Analysis Center at Watertown, Massachusetts, to provide increased and more rapid abstracting service to both DOD and industry.

3. Technical Problem Areas

The majority of the problems facing DOD are well characterized and could be handled best by the proper use of NDE during the development and manufacture of the material and the processing of the product. These problems require selecting test parameters, designing tooling, defining acceptance levels, and using more than one technique for evaluation. The fact that problems solvable by present technology are included with problems requiring innovative development

indicates the need for better communication between the experts in, and the users of, NDE services.

Automatic data processing equipment must be utilized to attain qualitative capabilities through rapid feedback of data for process control, utilization of all data, comparison with prior data for early detection of trends, and instantaneous comparison of data from the same material to evaluate operational changes.

Due to the limits of time, effort was directed to the following general problem areas which require extensive technique development or innovation. The problems are listed in a priority sequence established by the Committee according to the universality of the need, the recognition of practical approaches, and the likelihood of successful solution.

Joining: This group of five functionally-related problems is the objective for immediate study. (1) Welding requires more quantitative NDE techniques, lowering of the minimum detectable defect size, and imaginative new techniques of data acquisition and analysis. (2) The basic problem for adhesive (chemical) bonds and solid state (metallurgical) welds is evaluation of bond strength for which innovative development is needed. (3) Mechanical fastening and brazing appear to be problems of characterizing the specific joint design, tailoring existing new techniques to the specific problems, and, for certain configurations, innovations to allow evaluation in hidden locations.

Recommendations:

a. Conduct intensive development efforts on ultrasonic scatter detection methods, similar to the Delta Effect. Although conventional fusion weldments in steel and aluminum only need a detailed analysis of the specified requirements and of the economics of more exacting inspection, new NDE methods are necessary for welds of refractory materials and superalloys.

b. Pursue fundamental research in the physics of adherence as a prime objective in adhesive bonding, followed by the search for NDE methods that can be correlated with a parameter determining adhesive strength. Adhesive bond is a problem because of the need to know bond strength.

c. Determine ultrasonic transmission/reflection characteristics of various braze alloy/parent metal joints and correlate by destructive testing parameters measuring bond strength. Improve knowledge of the parameters producing strength in brazed bonds.

d. Study individually each configuration produced with mechanical fasteners since these problems are configuration-controlled.

Coatings: Advanced state-of-the-art methods are adequate for most coating problems, assuming careful characterization of the specific couple and configuration. Ingenious tooling and careful evaluation of limits for flaws are required for most coating problems.

Recommendations:

a. Develop extensively methods for detecting fine voids in sprayed metallic coatings. A promising approach appears to be the use of eddy currents created by a very high frequency and coils in the size range of 0.005 and 0.015 inches.

b. Create coating adherence evaluation techniques from the results of the research on physics of adherence (recommended under Joining) whose study is basic for all bond strength determination.

c. Define the accuracies and limitations of radiation backscatter, thermo-electric, and eddy-current methods to analyze a wide variety of coatings/substrate couples for both coating thickness and alloy composition uniformity (chemical and microstructural variations).

Composites: Glass-resin composites have received considerable study, and current applicable NDE methods need more industrial application. The newer composites, such as metal/metal, metal/ceramic, and graphite/resin have had relatively limited application of NDE in the determination of properties. In the development projects for new materials and components, funding should be

provided to permit the concurrent evaluation of and correlation between the signals obtained by nondestructive techniques and the material condition producing the signals and the effect of these conditions on the materials properties.

Recommendations:

a. Increase the current effort in characterization of composites using NDE methodology whose prime objective is the establishment of a thorough knowledge of the important material-energy interactions. occurring in the composite system being investigated, and the development of NDT methods and evaluating techniques enabling the prediction of elastic and mechanical properties of interest to DOD designers.

b. Study the basic scientific phenomena to create NDE methods to ascertain quantitatively and qualitatively the characteristics of composites of metallic fiber/metallic matrix, metallic fiber/nonmetallic matrix, and nonmetallic fiber/nonmetallic matrix.

c. Develop techniques to apply microwaves to all nonmetallic composites in order to evaluate material characteristics and to detect flaws, such as surface cracks, voids, and unbond.

d. Investigate frequency modulated ultrasound applied to highly attenuating composite materials as an evaluating technique for properties such as density, strength, and flaw detection.

Graphite and Ceramics: NDE techniques have been studied for a few nuclear and aerospace applications of bulk graphite. Laboratory work is well advanced for the detection of flaws in certain grades of materials and for the prediction of mechanical properties. Transition from laboratory techniques to industrial practice is needed. Generally, these materials are used in structures whose design precludes adequate evaluation after the installation of the graphite or ceramic component.

Recommendations:

a. Derive specification requirements during experimental projects for material and component development to establish process controls of the properties of these highly variable materials and to define qualitative and quantitative parameters.

b. Develop correlation between NDE data and service performance in structural applications.

c. Evolve methods to evaluate these materials after installation in an assembly and during service. Investigate frequency modulated ultrasound and acoustic emission as promising methods for detecting and monitoring cracks.

Alloy Verification: This problem has been ignored in spite of its importance and the availability of the necessary testing techniques. Alloys are specified for critical parts but rarely is any effort made to verify the alloy composition in the final part, although many opportunities exist for mixing of alloys.

Recommendations:

a. Enforce drawing requirements for alloy verification of finished parts.

b. Promote development of a portable, simultaneous reading x-ray spectrograph and calibration samples for rapid alloy verification.

Surface Cleanliness: Critical aerospace components frequently have stringent cleanliness requirements. Coating and bonding problems are dependent upon surface preparation, but our survey does not indicate the existence of objective, quantitative methods to evaluate surface cleanliness.

Recommendations:

a. Promote development of innovative methods, such as low energy electron reflections, to evaluate surface films and soils.

b. Sponsor studies for scanning techniques to evaluate surfaces for embedded, minute particles (as from

grit blasting) which would degrade the bonding of coatings, etc.

Residual Stress: The magnitude and sign of the residual stress in a part are areas of uncertainty in stress analysis. The current methods have limited applicability. A concerted effort is needed to adapt potentially applicable NDE techniques to the specific residual stress problems.

Recommendations:

a. Continue studies to correlate ultrasonic velocity measurements in the various modes with residual stress.

b. Study the applicability of polarized eddy-current probes in orthogonal coil configurations for the determination of residual stress.

Fatigue: Evaluation of incipient fatigue or remaining fatigue life is an old NDE problem. A concentrated interdisciplinary effort is required to identify precursors and to monitor fatigue progression.

Recommendations:

a. Identify precursors of fatigue cracks in terms of phenomena detectable by NDE techniques.

b. Study the chartability of the fatigue process using ultrasonic techniques to interrogate with two or more modes coupled with sophisticated data correlation methods.

Thin Materials: Instrument limitations have retarded application of NDE techniques to the evaluation of thin materials. Examples of needed apparatus development are: very high frequency eddy-current instruments, higher frequency and higher resolution ultrasonic instruments, and very low energy x-ray equipment.

Recommendations:

a. Conduct a survey to determine need and to define characteristics and limits for acceptance.

b. Assess the ability of available eddy-current equipment operating at 5 MHz and ultrasonic equipment operating at 25 MHz to meet the above requirements and develop improved equipment to meet the deficiencies.

Corrosion and Stress Corrosion: The state of the art is adequate for exposed surfaces, but no adequate approach exists for corrosion in blind areas or under protective coatings.

Recommendations:

a. Explore radiation back-scatter methods for the detection of corrosion products under protective coatings.

b. Study the applicability of ultrasonic scatter measurements, similar to the Delta Effect, coupled with data correlation techniques for the detection of such corrosion.

4. Special Phenomena

No new form of energy has been discovered recently which could have any immediate impact on NDE techniques. After reviewing current and new scientific phenomena for their applicability to NDE, studies in the programs below appeared most promising.

Recommendations:

a. Study failure mechanisms as applied to bulk materials and to bonded assemblies to determine which parameters measured by NDE techniques can be correlated with the properties and characteristics of interest.

b. Increase activity in the use of data processing as a correlation technique to characterize material-energy interactions in terms of basic material properties and to improve nondestructive evaluation.

c. Investigate lasers and holography intensively to assess their potential in NDE.

d. Initiate additional basic research in the area of acoustic propagation to gain a better understanding of the mechanisms of acoustic absorption and scattering.

e. Investigate the use of acoustic emission as an in-service inspection technique to reveal impending failure.

f. Hold periodic meetings of theoretical and applications oriented scientists from many disciplines to examine the utilization of new scientific developments in NDE.

II. INTRODUCTION

The nondestructive testing profession in the United States is about fifty years old. In 1922, this country's first industrial radiographic laboratory was installed at the then Watertown Arsenal by Dr. H. H. Lester as a tool for the development and improvement of steel castings for Army Ordnance components. In 1927, the Watertown Arsenal used radiography in its program to develop and to improve fusion welding techniques. From this beginning, until the start of World War II, NDE was either fostered or developed by various DOD agencies primarily as a process control tool. During World War II, NDE was used widely in inspection. The development of new methods and instrumentation was attributable directly to the requirements and to the leadership of DOD. Since World War II, the few professionals in NDE within DOD and industry have been working on the technical organization of their field and to the solution of immediate problems. This report examines the possibility of eliminating quality problems by building in inspectability during design as a necessary ingredient to improved product reliability.

Nondestructive evaluation (NDE) is a descriptive phrase applicable to noninjurious methods for measuring properties, and for detecting and measuring discontinuities, and defects of materials or parts. Quantitative values are obtained. for properties and defects, measured by these tests, when they are correlated by destructive testing and service experience. Generally, NDE has been applied qualitatively and as a mechanism for acceptance or rejection. NDE has evolved over the years to mean the use of any energy form which reacts with the interrogated material to produce useful data or intelligence without damaging the material. Classical examples are the recording of x-ray intensity variation on film to determine voids of a spherical geometry and the reflection of ultrasonic pulses from an internal laminar type defect. Much of the electro magnetic energy spectrum has been utilized, as well as mechanical and thermal energy and some forms of surface chemistry. Testing per se generates raw data which must be translated into the language of the materials and design engineers before the data can be useful. A major problem in DOD and industry is implementing the transition of NDT to NDEvaluation to gain full utilization of its potential.

III. GENERAL OBJECTIVES, SCOPE AND EXPECTED BENEFITS AND APPLICATIONS

Today, structures must be designed to utilize materials at the highest possible strength/weight ratios to maximize payloads for the increasingly exacting demands of sophisticated military systems. This need to use materials to their design limits imposes greater emphasis on quality control and reliability. For optimized use of both old and new materials, their quality must be established prior to, and during construction. The parts and structures should permit monitoring in critical areas during service to enable detection of such things as corrosion, increased stresses, and cracks and their growth to critical size. Nondestructive evaluation is the mechanism by which this could be accomplished.

The objectives of this study were (a) to determine critical areas in both the processing and operational phases, where NDE techniques are necessary; (b) to determine where present techniques are inadequate for the above areas; (c) to prepare approaches for eliminating or minimizing these inadequacies; (d) to construct a comprehensive and integrated plan embracing all pertinent factors; and (e) to stimulate the introduction of new concepts for major improvements in our NDE capability.

The study was to consider all types of equipment and techniques used in NDE, including unexploited phenomena which might contribute to advancing the technology. The study embraced many disciplines and covered the behavior of metallic and nonmetallic structural materials. The effort was envisioned as an aid in the development of new materials and their processing, and in the design of components and structures. The effort was to avoid only marginal improvements in instruments and techniques.

Many benefits were visualized as resulting from the study. A most significant contribution to all critical military construction and equipment would be the achievement of a mass plan for NDE, of new concepts and of major technical improvements. Increased reliability of materials and hardware, developed with the aid of suitable NDE techniques, would permit higher design values, in some instances, exceeding those obtainable from new materials which, if developed without NDE, would have lower design values. These expected benefits would contribute to the achievement of missions and to better cost effectiveness.

IV. GENERAL DISCUSSION

Failure of military, aerospace, and industrial hardware is the consequence of many variables, chief among which are:

(1) Inadequate definition of service stress;

(2) Poor design decisions failing to provide required strength;

(3) Faulty execution of manufacturing processes in producing the designed component, and

(4) Extension of the use of the hardware beyond the design intent.

Nondestructive evaluation can contribute significantly to a solution of many reliability problems by providing quantitative, diagnostic results, an improvement over human assumptions. However, the designer must specify the requirements and the necessary tests.

The Committee estimated that approximately 20% of today's recognized NDE problems have existed for ten to twenty years and are unsolved, for one of two reasons:

(1) The problem has been identified but not defined in sufficient detail to permit intelligent research toward its solution; or

(2) Novel NDE techniques are required beyond those currently available.

The first category requires a study of failure mechanisms to define the problem: the second category requires research on the scientific disciplines involved in NDE methods to yield novel approaches to a solution.

After a comprehensive review of the technical NDE problems as delineated by Service inputs, it appeared that 80% of the problems could be resolved by good engineering application of existing knowledge. Some 20% of the problems, such as bond strength, have been recognized for twenty years or more as requiring a basic research effort for solution.

While the Committee emphasized that 20% of problems required novel NDE methods derived from research, it believed that this research would solve no real hardware reliability problems unless the engineering effort was made concurrently to assure implementation. To incorporate the needed engineering into hardware design and fabrication, NDE must be specified as an integral part of quality/reliability planning. A general specification on the application of nondestructive evaluation was considered the mechanism for applying NDE to design-production-service cycles.

The failure to achieve solutions to existing problems in the 80% category could be directly attributed to the acute shortage of NDE engineering personnel both in DOD and industry and to the lack of NDE implementation. Since there is no formal academic training available at universities in NDE at the Bachelor's level, the comparatively few professionals in the field are the result of recruiting from other disciplines.

Study of DOD's Project Hindsight* indicated that:

(1) The growth of knowledge in any area was directly related to the number of scientists and engineers involved therein;

(2) In addition to the importance of the number of scientists and engineers involved, the relative levels of their educational achievements were a factor; and

(3) The best performance came from the more stable personnel.

The Committee believes that a new specification philosophy will stimulate demand for trained personnel. This, in turn, will influence universities to develop the needed professionals. In addition to assuring a supply of trained engineers, the implementation of the Committee's detailed recommendations would result in a considerable fiscal economy to DOD in terms of increased component and system reliability.

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* Isenson, R.S., "Technological Forecasting Lessons from Project Hindsight," pp 35-54, Technological Forecasting for Industry and Government, James S. Bright, Ed., published by Prentice-Hall, Inc., Englewood Cliffs, N.J. (1968).

A first-class information storage, retrieval, and analysis center is imperative for the efficient utilization of research and of engineering manpower. Such a center is the most economical form for collecting and disseminating information.

The above points are discussed in greater detail in their respective sections.

SECTION II

Education and Promotion

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FOREWORD

The common role of the university embraces several functions: (1) The generation or discovery of new knowledge; (2) The organization and codification of that knowledge; and (3) The dissemination of that knowledge through teaching and publications. As has happened so many times in the last fifty years, the needs in a professional area have outstripped the capability and willingness of the educational institutions to satisfy the demand. Frequently, the lack of willingness is due to the failure of the responsible leaders in the universities to recognize the need as a legitimate field of scientific investigation. This seems to be the situation relative to nondestructive evaluation. This section summarizes the current situation relative to provision for education in nondestructive evaluation, and presents some recommendations for the immediate and long-range improvement in this situation. The improvement in the educational program will require carefully planned promotion on the part of Government and industry, and the financial support for research and course development. This section concludes with recommendations for the development of the promotional programs.

CONTENTS

ABSTRACT

In order to produce more well-qualified nondestructive evaluation (NDE) engineers, American universities must be convinced that nondestructive evaluation is a science relying upon the most advanced knowledge in fields such as physics, materials, and electronics. Then, hopefully, these institutions will incorporate this subject into their curricula and graduate well-qualified and greatly-needed NDE engineers. An intensified educational program for technical management is of paramount importance to aid them in implementing their responsibilities. The establishment of national NDE research centers for and by Government agencies is also highly recommended.

I. INTRODUCTION

Many statements and recommendations in this section have been made in the past. To date, management in Government and industry has not awakened to the alarming shortage of personnel qualified in nondestructive evaluation and has not provided the financial support in the interest of national welfare, public safety, and economy. Thus American educational institutions have not realized that NDE is a science utilizing the most advanced concepts in disciplines such as physics, chemistry, metallurgy and electronics. Properly educated and trained personnel must be constantly motivated and kept abreast of advanced concepts, techniques, and equipment to improve quality control and reliability assurance.

The American Society for Nondestructive Testing has contributed to the progress, to the knowledge, and to the role of NDE in industrial applications. Twenty-three industrial nations have formed an International Committee for Nondestructive Testing and have sponsored five international conferences since 1955. Through these international activities, knowledge is being disseminated and specifications, standards, and codes are understood better universally.

II. EDUCATION

1. The Educational Challenge of Nondestructive Evaluation

The success of an organized NDE educational program depends almost entirely upon the ability to educate a large number of engineers and technicians in the field. Special efforts by industry, Government, and educational institutions are needed to inform students and workers of the opportunities in this area. To date, activities of the various technical societies, such as the American Society for Nondestructive Testing, the American Society for Testing and Materials, and the American Society for Materials, have not stimulated colleges and universities to produce the engineers and scientists needed in NDE.

Educational programs should cover at least four levels of sophistication:

1. The technician level.
2. The engineer level.
3. The research scientist level.
4. The technical management level.

The technician level calls for an innate intelligence and aptitude. The minimum educational requirement should be a high school diploma plus training in such areas as equipment, procedures, electronics or related subjects. Two-year junior colleges or technical institutes could provide such formal education. On-the-job experience and/or apprentice training should be additional requirements. The combination of these two phases of education can then lead to the qualification and certification of NDE personnel along the lines described in the document, Recommended Practice No. SNT-TC-1A, published by the American Society for Nondestructive Testing.

Most of the education in this area is the result of manufacturers' efforts and on-the-job training. Current educational courses for technicians are very inadequate. They range from a few days to six weeks in length. Practically no formal educational prerequisites are required; no tests are given, but certificates generally are issued. The extensive fees for such courses plus their meaningless certificates create an aura of expertise far beyond that developed by the participants. A number of such courses and training programs are listed in Appendices A and B.

The minimum requirement for the engineer level should be a Bachelor of Science degree in an appropriate engineering field, plus several years of special training. A Master's degree would be an asset, particularly if the program included theoretical aspects of NDE. Experience should also be required in quality assurance and management and in the comprehension and correct implementation of test specifications, data analysis, and specification preparation.

Education in NDE at the university level is almost nonexistent. A major change is not anticipated in the foreseeable future because university administrators and faculty members are generally unaware of the existence of this important tool in modern technology. Due to inadequate budgets, these institutions of higher learning veer from subjects that call for major expenditures in the form of laboratories and new equipment. Because of the preference for faculty additions with Ph. D. degrees and theoretical backgrounds, and since the most knowledgeable individuals in NDE

are currently industrially trained engineers without Ph. D. degrees, a knowledge gap of severe proportions is created between the universities and industry which requires experience in applied sciences.

The research scientist level should require graduate work in materials science, physics, mathematics, and statistics as well as in the specific areas of NDE. Undoubtedly, a Doctoral degree, following a broad undergraduate education in the sciences and mathematics, would be the best preparation for a career in the research and development of NDE theory and techniques.

Being unfamiliar with the scope of NDE, no universities offer Ph. D. programs in this field. Through organized coordination and knowledge of the demands of the NDE profession, a firm foundation could be established toward advanced degrees in this field. Courses and laboratory facilities, already in existence but scattered through the various departments of the universities, could be organized to produce effective curricula for graduate degrees. Professors should be encouraged to take leaves of absence to work in industry or Government agencies not only to advance their careers but to familiarize themselves with the needs and potentials for research scientists with advanced degrees in NDE.

Members of the technical management level in industry and Government, particularly those entrusted with the design, quality assurance, and serviceability of military hardware, must have a better knowledge and appreciation of this all-important field. Unfortunately, the vast majority of these decision-making members are unfamiliar with the rapidly growing role of NDE in modern engineering and technology. This lack of knowledge is reflected in many phases of industry's endeavors such as budgetary considerations, selection of equipment and manpower, establishment and delegation of meaningful responsibilities, and the incorporation of NDE capabilities in research, development, and design. Often this results in technically incompetent individuals being involved in solving the problems in this field.

Many universities now sponsor seminars on NDE and employ visiting lecturers. These institutions should use such courses to educate their staffs on the importance of the subject and to develop viable NDE departments.

The establishment of NDE programs in colleges and universities would enhance NDE's scientific stature, a very necessary development for its growth. This emerging visibility would serve to acquaint other scientists with NDE problems and should profitably increase the interplay between the various disciplines, such as physics, chemistry, and materials science, which contribute heavily to and are involved in NDE.

2. Summary of Conclusions and Recommendations

Conclusions

1. Members of technical management, particularly those concerned with design, quality assurance, and serviceability of hardware are not fully aware of the rapidly-growing role of NDE in modern engineering and technology.

2. Generally, educational institutions do not have the interest, staff, or funds to establish and to staff the NDE departments needed to produce the people required by Government and industry. This dearth of capable personnel extends down through the technical level.

3. Individuals most knowledgeable in NDE are currently industrially trained engineers without Ph. D. degrees, generally unacceptable as faculty members by universities.

4. The shortage of qualified personnel at all levels cannot be alleviated without Government financial support to educational institutions.

Recommendations

It is recommended that the Department of Defense in concert with other Government agencies sponsor educational programs to produce the technicians, engineers, research scientists, and technical management necessary for our Government and industrial requirements.

1. Fund technical institutes and junior colleges to provide the laboratories and staff to train technicians.

2. Provide grants to universities to establish laboratories and staff for at least five years to assure continuity of programs.

3. Establish scholarship and fellowship grants, competitive in funding with those currently available to the sciences, to attract highly competent students to this new field at the undergraduate and graduate levels.

4. Stimulate personnel concerned with NDE to keep abreast of advances in technology.

III. PROMOTION

1. The Need for Promotional Activities

Primarily, four major groups can benefit greatly from the promotion of NDE. Logically, therefore, their technical managements have the responsibility to foster and to promote NDE at all levels of engineering, design, development, and production. These four groups are:

1. DOD and other Government agencies;
2. Materials producers and product fabricators;
3. NDE equipment manufacturers;
4. Management of research, development, production engineering and design departments.

Professional societies such as the American Society for Nondestructive Testing, the American Society for Testing and Materials, and the American Society for Mechanical Engineers constitute a common meeting ground for representatives of these groups. There technical information is disseminated, and codes, standards, and specifications are born.

The design authority (who has the responsibility for specifying the necessary NDE requirements) is the principal key to the promotion and use of NDE. Only designers educated in the capabilities of NDE can establish fruitful communications between effective design review teams and NDE specialists. Such communication

will automatically influence the thinking of fabricators, manufacturers and ultimately of the designers of NDE equipment.

2. <u>The Principles Guiding Promotional Activities</u>

The Committee wishes to list some of the principles upon which the section on Promotion is written:

1. Correct application of NDE renders benefits in improved safety, high reliability, and economy.

2. When using these methods expertly, the officially known "Safety Factor" (its true name "Factor of Ignorance") can be decreased. This progress in the field of materials engineering consequently gives the designers greater freedom for innovation and advanced designs.

3. Designers must project NDE methods in basic design considerations, fabrication and service requirements.

4. Designers must require effective in-service inspection and testing to assure continuance of reliability, serviceability, and in-service monitoring and testing.

5. Applicable NDE methods must be used to evaluate the defects of identified failure mechanisms.

6. Technical management must recognize NDE as a basic tool for implementation of its policies with quantitative justification based on economic costs and benefits over the entire lifetime of their product.

7. Properly educated personnel must be motivated and must keep abreast of advanced concepts, methods, equipment, and techniques for attaining the desired yield of NDE.

8. NDE personnel must be continuously motivated and stimulated to assure continuity, interest, best efforts, and improvement in quality control and reliability assurance. Maintaining the status quo cannot keep test systems up-to-date in an atmosphere of advancing technologies.

9. Required NDE systems should be developed when new materials, fabrication processes, designs, or service applications are in the state of research and development and not when crises develop.

10. Should little or no attention be given to the above listed principles, the consequences could range from minor breakdowns and delays to major catastrophes which include such disastrous consequences as waste and loss of material, economic setbacks, loss of valuable time, decreased reliability not only of the manufacturers' product but also of professional integrity and know-how, loss of lives and in extreme cases loss of the technological reputation of the nation. Many such cases during the last fifteen to twenty years are horrible examples for, and continuously reminding witnesses to these statements.

3. Recommendations for Promotional Activities

The Committee, therefore, recommends that the Department of Defense develop a promotional program in conjunction with the professional societies and the Government agencies on the following fronts:

1. Establish and fund centers of excellence for research and development in NDE by grants from Government and non-Government agencies. These centers should conduct both pure research (to find or to improve theories and knowledge) and applied research (to establish the means for utilizing new knowledge in solving real problems).

These centers should also be charged with the dissemination of new knowledge through established channels.

2. Encourage the publication of well written articles of educational nature to inform engineers, designers, and managers regarding the most modern NDE methods, the respectively available tools and equipment, and data analysis.

APPENDIX A

SHORT COURSES IN NDE--EARLY 1968

Company	Subject
Agfa-Gevaert, Inc. Teterboro, New Jersey in cooperation with ASNT	Up to 6 weeks course on NDE
Automation Industries, Inc. Sperry Products Div. Shelter Rock Road Danbury, Connecticut	Magnetic particle--Ultrasonic, Eddy Current Ultrasonic Radiography
Balteau Electric Corporation Stamford, Connecticut	For users of Balteau equipment Seminars 2 to 3 days
Branson Instruments, Inc. Progress Drive Stamford, Connecticut	Ultrasonic
Budd Instruments Division* Phoenixville, Pennsylvania	Theories, techniques and uses of ultrasonics, eddy current, radiography, strain gages, photoelastic stress analysis.
Convair Div. of General Dynamics NDT Training School, Dept. 149-00 San Diego, California	Radiographic Testing (40 hours) Eddy Current Testing (40 hours) Ultrasonic Testing (40 hours)
Eastman Kodak Company School of Industrial Radiography Department 741 Rochester, New York	Radiography
Krautkramer Ultrasonics, Inc. One Research Drive Stamford, Connecticut	Ultrasonic
Magnaflux Corporation Chicago, Illinois	Magnetic particle, Magnetic penetrant, Ultrasonic
Picker Corporation Industrial Products Division White Plains, New York	Radiography

The foregoing material was extracted from "The Pressure Builds for Nondestructive Testing: Codes, Liability, Education," Welding Design and Fabrication, February 1968, pp. 51-66, except for the Convair entry.

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* Now part of Automation Industries, Inc.

APPENDIX B

NDE COURSES BY UNIVERSITIES, JUNIOR COLLEGES, AND HIGH SCHOOLS

Four-year colleges and universities offering credit courses devoted soley to NDE:

University of Arizona
California State Polytech
Indiana State University
Louisiana State University
Lowell Technical Institute
University of Missouri
Ohio State University
Sacramento State College

Four-year colleges and universities offering credit courses devoted partially to NDE:

University of Bridgeport
Carnegie Mellon University
Chattanooga State Technical Institute
Fresno State College
University of Hartford
Lehigh University
University of Missouri*
University of New Hampshire
Ohio State University*
Old Dominion College
Pennsylvania State University
Stout State University

* See above list also

Other four-year colleges and universities having courses listed by article, "The Pressure Builds for Nondestructive Testing: Codes, Liability, Education," Welding Design and Fabrication, February 1968, pp. 51-66.

University of Washington--16 hours of NDE courses
Drexel Institute of Technology--3 evening courses in modern welding and welding metallurgy
Illinois Institute of Technology--2 week short course (workshop) in NDE, summer
University of Wisconsin--NDE as part of welding curriculum
Institute of Nondestructive Testing, Milwaukee School of Engineering--2-year Associate of Arts degree in NDT.

Other schools offering Associate of Arts degrees in NDT are shown on the next page.

High School Technical Training Courses:

Don Bosco Technical Institute
Texas A&M University Extension Service
(See following pages)

SUMMARY OF 4 YEAR COLLEGES AND UNIVERSITIES

School	Full NDT	Partial NDT	Short Course	% if Partial	Usual Enrollment/Yr. Full--Partial--Short			Class Laboratory	NDT Research
U. of Arizona	x				50			x	x
U. of Bridgeport		x		4%		25		x	
Cal. State Poly.	x				-			x	
Carnegie Inst. Tech.		x		5%		40			
Chattanooga State		x		5%		20		x	
Fresno State Col.		x		16%		25			
U. of Hartford		x		-		60		x	x
Indiana State U.	x				10			x	x
U. of Iowa	x				15			x	x
Lehigh U.		x		5-10%		25		x	
La. State U.	x		x		20		15	x	x
Lowell Tech. Inst.	x				20			x	
Mass. Inst. Tech.			x				40	x	x
U. of Mo. (Rolla)	x				50-100				
U. of Mo.		x		5-10%		5-20			x
U. of New Hampshire		x		5-10%		20		x	x
Northeastern U.			x				50		
Ohio State U.	x	x	x	10%	18	180	40	x	x
U. of Oklahoma			x				-		
Old Dominion Col.		x		20%		60			
Penn. St. (Beaver)			x				15		
Penn. State U.		x		10%		25-70		x	x
Sacramento St. Col.	x							x	x
Stout State U.		x		10-15%		20-30		x	
U. of Wisconsin			x				50		

Information by courtesy of the ASNT, Liaison Division, Educational Council, Preliminary Report, March 1968

ASSOCIATE DEGREE LEVEL CREDIT COURSES IN NONDESTRUCTIVE TESTING

School--Department	Age	Contact hrs/wk	% NDT	Student No.	Laboratory Activity	Outstanding Needs Long-Range Plans
Brevard Jr. College Q. C. and Reliability	2	17 weeks (51 hrs)	100	15-25	Field trips Demon- strations	---
Chattanooga State Technical Institute Mech. Technology	2	24 wks	5	15	X-ray unit on order	Industrial Displays
Contra Costa Jr. College	new	-----	100	---	Extensive	Publicity--Needs students
Erie County Tech. Inst. Metallurgical Tech.	-	12 wks 6 hrs/wk	100	50	Extensive	Text; teaching aids
Highline College	1	17 wks	100	---	-----	---
Milwaukee School of Eng. Institute for NDT	-	-----	100	---	Extensive	In organizational phase
Temple University Technical Institute Metallurgical Tech.	2	15 wks 2 hrs/wk lecture 3 hrs/wk lab course	100	 15-25 15-20	 Extensive	Also given to short course certificate students
San Diego Jr. Colleges Quality Control and Reliability	7	2 yr. course 60 units for A. S. degree	25	25-35	Some	Need laboratory facilities

ASSOCIATE DEGREE LEVEL CREDIT COURSES IN NONDESTRUCTIVE TESTING

School--Department	Age	Contact hrs/wk	% NDT	Student No.	Laboratory Activity	Outstanding Needs Long-Range Plans
Corritos College Metallurgy	2	64 hrs	100	28	Magnetic penetrant	---
Shoreline Community College Quality Control	1	11 wks 33 hrs	100	20	Field trips	Equipment & Laboratory
T. H. Harris Vocational Technical School NDT Tech. Dept.	3	18 mos 1500 hrs	100	20-40	Extensive	Text; Equipment

HIGH SCHOOL--TECHNICIAN TRAINING COURSE

School--Department	Age	Course Length	Student No.	Laboratory Activity	Outstanding Needs Long-Range Plans
Don Bosco Tech. Inst. Metallurgy	11	1 semester 12.5 hr/wk	-----	Extensive	Expand into a course dealing specifically with NDT. Possibly organize a 2-year Associate Degree course.
Texas A & M Univ. Engineering Extension Service	$1\frac{1}{2}$	16 wks	12	Extensive	This is a course in radiography. Would like to offer courses in other NDT techniques.

Information by courtesy of the ASNT, Liaison Division, Educational Council, Preliminary Report, March 1968.

SECTION III

Information

MEMBERSHIP OF THE PANEL

G. M. Corney, Chairman

D. E. Driscoll

F. S. Williams

FOREWORD

The collection and dissemination of information is an acute problem in all technical fields, and particularly so in nondestructive evaluation. Since the consequences of neglect of this phase can be so grave, the sources of, and the repositories for, information on nondestructive evaluation were reviewed with particular attention to the present and future needs of the Department of Defense.

CONTENTS

ABSTRACT

Nondestructive evaluation (NDE), in its current state, is a highly developed technology. The techniques now used, along with an indication of their applicability, are given in an outline form adapted from Materials Advisory Board Report MAB-231-1.

This technology is supported by an extensive technical literature. Unfortunately, by the nature of the field, such literature is widely diffused. Therefore, lists of useful information sources--texts, journals, "information centers"--are supplied in this section of the report.

It is essential to the needs of the Department of Defense (DOD) and the Nation that knowledge both of current techniques and of new developments be quickly available to those engaged in research, development, production, and field service of materiel. The most economical mode of collection and dissemination of this knowledge is through an "information center." Fortunately, the Department of Defense already has such a center--the Nondestructive Testing Information Analysis Center at Watertown, Massachusetts. Specific recommendations are made as to how the activities of this center can be expanded to increase greatly the awareness within DOD of the valuable material contained therein.

I. INTRODUCTION

One of the main problems in any technical field is the dissemination of information--"old" information concerning established techniques, and "new" information about new techniques and refinements of existing ones. Lacking such dissemination, work may be duplicated, money and material wasted, and lives endangered because known solutions may not be applied to existing problems.

The problem is particularly acute in nondestructive evaluation (NDE) because NDE cuts across many different disciplines. As a consequence, research, development, and application of current or new techniques may be largely duplicated in university departments of chemistry, physics, or engineering, and in industrial divisions of research, development, or production. This broad diffusion of interest naturally leads to a broad diffusion in the technical literature.

This section outlines the current nondestructive evaluation methods and lists briefly books and periodicals of particular value. Recommendations are made which will facilitate the flow of nondestructive evaluation information within the Department of Defense and which will promote person-to-person contact--often the quickest and most efficient method of solving a technical problem.

II. DISCUSSION OF INFORMATION DISSEMINATION

1. Current Techniques for Nondestructive Evaluation

Current methods for nondestructive evaluation were recently outlined in tabular form by the Committee on Aerospace Manufacturing Requirements (CAMR) of the Materials Advisory Board, Division of Engineering-National Research Council. The NDE techniques and attributes measured, or inspected, are listed in Appendix A and are adapted from Materials Advisory Board Report, MAB-231-1. The lettering and numbering system used in that report has been retained to facilitate cross reference.

Upon examination of the list, it will be clear that no attempt has been made to provide a handbook of nondestructive evaluation, but rather, an outline of techniques which are available to the trained practitioners thereof.

Note that the mention of a technique or technology in the material below by no means implies that all associated problems are solved. Some techniques, indeed, are in the early developmental stages. Without exception, all will repay further research, both on the equipment and procedures involved, and on application, limitations, and interpretation of indications and data.

2. Nondestructive Evaluation Publications

Books

With such a variety of nondestructive evaluation techniques already in use, it would be neither possible nor appropriate to attempt herein a complete list of publications in the field.

The books in Appendix B, however, will be found useful as sources of practical and theoretical information. (The list is restricted to English and has been started with the publication date of 1959. Thus, in the interest of brevity, many worthy publications have been arbitrarily excluded. Further, omission of a book from this list is not to be construed as a criticism.)

Technical Periodicals and Abstract Journals and Services

Information on current developments, discoveries, and applications in nondestructive evaluation is contained in periodicals. As pointed out in the Introduction to this section, pertinent information will be found in an exceedingly large number of technical journals. For this reason, a complete list of these journals would be impossible. However, a survey of the *ad hoc* Committee on Nondestructive Evaluation shows that the journals listed in Appendix C are among the most valuable. A separate list of abstract journals and services are also given in Appendix C.

Literature and Information Sources For "New Phenomena"

The January 25 and 26, 1968, meeting of the Panel on Special Phenomena is described on pages I-v and V-2 of this report. The guests at this meeting, representing a wide range of disciplines within the physical and chemical sciences, were asked by questionnaire for the best sources of information on the potential application of "new phenomena" to the future development of nondestructive evaluation techniques. The replies to the questionnaire (about 24%) are listed in Appendix D.

3. Information Centers

One of the best means for making available the information--past and current--on a technical field is the "information center." This is an organization whose function is to collect, index, and disseminate information and data on a particular field.

Such activities have become increasingly important over the past twenty years. At present, often the first publication of technical information--and not infrequently the only publication--is in the form of a report from a Government activity or from one of its contractors. Aside from the question of security classification, these reports are outside the traditional channels of scientific communication. Therefore, they are frequently overlooked by, or are unknown to, abstracting sources and the like.

Information centers are doubly important in the field of nondestructive evaluation where much of the research effort is Government-supported (and perhaps classified), and which cuts across many disciplines. Thus, only a small fraction of the pertinent open literature may be easily available to a single investigator, institution, or production facility. Centers for general technical information, many of which deal with NDE, are listed in Appendix E.

There is only one information center in the United States dealing exclusively with nondestructive evaluation--DOD's Nondestructive Information Analysis Center at the Army Materials and Mechanics Research Center, Watertown, Mass.

The center at Watertown provides abstracts on specific NDE subjects when requested by the Services. A newsletter is also disseminated from Watertown whenever a quantity of new information on NDE has been accumulated. There are only a few centers of this type in the entire world, and they are listed in Appendix E.

In addition, there are many information sources whose purpose is to disseminate technical information in materials science and technology. Much of the collected information is related to the technology of NDE and can be of great help in specific instances. A representative listing of industry, universities, Government centers, and research establishments is given in Appendix E, although it is recognized that other information services may have been unintentionally omitted.

An excellent directory of information resources in the United States is published by the National Referral Center for Science and Technology and is available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402. Complete coverage of the functions of each of the information resources presented here would be redundant; therefore, only the official name and address are presented for guidance.

4. Informal Personal Contact

Analysis of the study, Project Hindsight, disclosed most interestingly the importance of informal person-to-person contact as a means for disseminating ideas and information. Such contacts appeared to be as effective as the published literature. The implications, therefore, are that technological growth is highly responsive to easy communication between the scientists and engineers of various disciplines and that technical publications are inadequate as the sole media for the interchange of thoughts and opinions.

For rapid solution of NDE problems within the U.S. Army Materials Research Agency, Watertown, Massachusetts, the Command uses individuals from its "Key Personnel Chart--Test and Evaluation Methods." An expanded list of this type could be employed to select experts for visits and lectures on NDE to universities, industrial organizations (particularly DOD contractors), or to technical societies. This list could also be useful as a source of authors for the educational articles mentioned in the promotion recommendations in Section II.

II. SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The presently-used nondestructive evaluation techniques cover many disciplines and are supported by an extensive technical literature. Access to the literature, however, is often awkward and expensive in time and money. This access can only become more difficult and expensive as new techniques are developed and are transferred from research to production. Any improvement in accessibility to the literature will result in savings of time, money, and potentially human life. Recommendations for improving this access, through the greater use of "information centers," are enumerated.

Recommendations

In common with other technical fields, nondestructive evaluation has an "information problem." A solution to this problem is important particularly to the Department of Defense and to others for rapid personal communication on technical points. Therefore, the Committee on Nondestructive Evaluation makes the following recommendations:

1. Expand the activities of DOD's Nondestructive Information Analysis Center (Army Materials and Mechanics Research Center, Watertown, Massachusetts), the only information center in the United States devoted solely to NDE. Sufficient technical and clerical help should be provided so that coverage of the literature can be expanded as rapidly as needs arise, so that computer-retrieval systems can be inaugurated, if necessary, and so that other activities, mentioned in the following recommendations, can be undertaken.

2. Give wider publicity to the existing information centers. It is important that the functions and the values of information centers be made known to those whose chief concern is

production and maintenance, as well as to those concerned with research and the handling of information and data. Where access to Department of Defense (and other Government) information centers can be granted to non-Government organizations, this publicity should be widespread in the technical and scientific press.

3. Encourage information centers to publish acquisition lists. If these ·uld include abstracts, their value would be increased manyfold, but a mere listing of titles would be a tremendous help. Because of the interplay and mutual support among military, other Government, and civilian technologies--particularly in NDE--in many cases, two lists would be desirable. One should include all literature, and the other, only open literature with appropriate circulation lists for each.

4. Maintain a current index of NDE experts with the Department of Defense. Ideally, the listings should be both by fields of special competence and location or branch. An example is the "Department of Defense Key Personnel Chart--Test and Evaluation Methods," prepared by the Army Materials Research Agency in May 1966. Since other divisions of the Government (i.e., NASA, AEC) are also strong in NDE talent, inclusion of these personnel would be highly desirable. Whether the index should take the form of a periodical (yearly ?) publication, or a file which could be consulted by telephone or correspondence, would depend upon the size of the file and the availability of the staff.

APPENDIX A

EVALUATION

Nondestructive Techniques

Adopted from CAMR

A. Visual
- AA. Optical techniques
  - AAA. Unaided eye
  - AAB. Aided eye
  - AAC. Light-sensitive instruments

    Attributes measured or detected
    1. Surface flaws
    2. Color
    3. Gauging
    4. Film (oxide) thickness
    5. Crack depth
    6. Surface finish
    7. Dimensions
    8. Reflectivity
- AB. Fluid penetrant technique (use of low viscosity, low surface tension fluids, which enter surface discontinuities by capillary action, aiding visual examination)
  - ABA. Liquids (alcohols)
  - ABB. Dyes (fluorescent-visible)
  - ABC. Gases
  - ABD. Filtered particle

    Attributes measured or detected
    1. Surface flaws
    2. Through cracks
- AC. Strain-sensitive coating technique (use of coatings whose appearance changes due to strain)
  - ACA. Birefringent
  - ACB. Brittle lacquer

    Attributes measured or detected
    1. Surface flaws
    2. Strain distribution and magnitude

B. Penetrating radiation (including x ray, gamma rays, electrons, neutrons)
- BA. Radiography and fluoroscopy (use of differential absorption of radiation to produce an image of internal structure)
  - BAA. Radiography (permanent image)
  - BAB. Fluoroscopy (transient image)

<u>Attributes measured or detected</u>

1. Flaws (voids, inclusions, shrinkage and cracks)
2. Assembly errors (misalignment, missing parts, foreign objects, separation in bond layers)
3. Gross density and chemistry variations (segregation, microporosity)
4. Dimensions (thickness or spacing)
5. Function (dynamic performance observation and process studies)

BB. Gauging techniques (use of transmitted or scattered radiation whose intensity correlates with thickness or composition)

BBA. Transmission techniques (source and detector on opposite sides of material under test)

BBB. Back-scatter techniques (source and detector on same side of material under test)

<u>Attributes measured or detected</u>

1. Density
2. Thickness
3. Distribution of components
4. Fluid level
5. Movement of tracer components

BC. Composition and structural analysis techniques

BCA. Diffraction techniques (use of coherently scattered radiation from object to indicate crystal structure and lattice spacing)

BCB. Spectroscopy (use of radiation excited in material under test to indicate composition)

<u>Attributes measured or detected</u>

1. Surface strain
2. Crystal structure analysis
3. Identification and measurement of constituents

C. Magnetic and electrical (use of magnetic and electrical fields to evaluate properties, and changes in properties, of materials)

CA. Magnetic leakage field technique (use of magnetic-field perturbations to detect discontinuities in ferromagnetic materials)

CAA. Magnetic particles

CAB. Magnetic tape

CAC. Probe scanning

<u>Attributes measured or detected</u>

1. Flaws - cracks, seams, inclusions, shrinkage, cavities, laps, hot tears, flakes, etc.
2. Local cold work due to bending, machining or other strain producing operations

3. Changes in hardness, alloy content
4. Distribution of austenite/ferrite

CB. Electromagnetic field induction technique (use of induced magnetic fields to evaluate properties of conducting materials)

CBA. Eddy current

CBB. Core loss

CBC. Potential drop in magnetic fields (Hall effect, magneto-resistance effects)

Attributes measured or detected

1. Cracks, crack depth measurement, laps and folds
2. Section thickness and thickness of layers over substrates; displacement or spacing
3. Degree of heat treatment; composition, segregation or contamination; orientation of anisotropy; corrosion and degradation of properties; hardness and tensile strength; electrical and thermal conductivity; cold work, etc.

CC. Potential drop technique (use of resistivity or potential-drop measurements to evaluate conducting materials)

CCA. Resistivity

Attributes measured or detected

1. Flaws, crack depth, unbond
2. Composition and variations in composition
3. Thickness

CD. Dielectric technique (use of electromagnetic fields, DC to 10^{11} Hz, to evaluate nonconducting materials)

CDA. Corona discharge

CDB. Electrified particle

CDC. Spark discharge

CDD. Dielectric analysis

Attributes measured or detected

1. Voids, separations, cracks
2. Uniformity of composition
3. Strength, state of cure, anisotropy, hardness
4. Thickness and linear measurement
5. Moisture content
6. Degree of cure, molecular weight, polar moments, crosslink chain flexibility, backbone-chain flexibility, etc.

CE. Magnetic resonance (use of magnetic properties of nuclei or atoms to determine properties of materials)

- CEA. Nuclear magnetic resonance
- CEB. Nuclear quadrupole resonance
- CEC. Electron paramagnetic resonance

Attributes measured or detected

1. Ion concentrations
2. Crystal structure
3. Composition
4. Molecular structure
5. Lattice strain

D. Mechanical vibrations (sonic and ultrasonic)

DA. Induced vibration technique (use of forced vibration or of mechanical waves)

- DAA. Pulse echo
- DAB. Through transmission
- DAC. Resonance

Attributes measured or detected

1. Flaws (cracks, voids, inclusions, unbonds, delaminations)
2. Elastic properties (moduli, Poisson's ratio)
3. Tensile, shear and compressive strength (of low ductility materials)
4. Distribution and amount of fillers and reinforcements (in composites)
5. Damping factor
6. Density, size and distribution of porosity
7. Structure (grain size, phases, shape)
8. Radiation degradation
9. Degree of cure and molecular structure (of plastics)
10. Dimensions
11. Degree of sintering, pressing, impregnation
12. Fluid contaminants
13. Viscosity
14. Liquid levels
15. Surface stress

DB. Self-generated vibrations

- DBA. Acoustic emission (use of sound generated by loading of a body to evaluate load or deformation due to load)
- DBB. "Ringing" techniques (use of the natural frequency of vibration of an object to evaluate properties)

Attributes measured or detected

1. Presence of discontinuities
2. Initiation and propagation of cracks
3. Leak detection
4. Malfunction (wear, misalignment, mechanical deterioration)
5. Size

E. Thermal

EA. Contact devices (use of thermal conductivity to evaluate properties)

EAA. Thermocouples

EAB. Thermistors

EAC. Thermometers

Attributes measured or detected

1. Plating thickness
2. Composition
3. Thickness
4. Inclusions
5. Voids
6. Leaks
7. Bonding
8. Porosity
9. Stress
10. Thermal conductivity
11. Heat contours

EB. Sensitive-coating techniques (use of surface temperatures to evaluate properties)

EBA. Sharp melting point compounds

EBB. Color change compounds

EBC. Thermographic phosphors

Attributes measured or detected

1. Plating thickness
2. Composition
3. Thickness
4. Inclusions
5. Voids
6. Leaks
7. Bonding
8. Porosity
9. Stress
10. Thermal conductivity
11. Heat contours

EC. Thermal radiation technique (use of infrared radiation from object to evaluate properties or function)

ECA. Photography

ECB. Infrared radiometers

<u>Attributes measured or detected</u>

1. Plating thickness
2. Composition
3. Thickness
4. Inclusions
5. Voids
6. Leaks
7. Bonding
8. Porosity
9. Emissivity
10. Reflectivity
11. Remote temperature sensing

F. Chemical and electrochemical

FA. Macroetch technique (use of chemical reactions to render surface details visible)

FAA. Swab or immersion technique

<u>Attributes measured or detected</u>

1. Surface flaws, cracks, porosity, inclusions, flakes, etc.
2. Macro structure, grain size variations
3. Gross composition, variations, segregation
4. Decarburization and carburization

FB. Spark oxidation test (use of color, form and life of grinding sparks to determine composition)

FBA. Abrasive wheel

<u>Attributes detected</u>

1. Type of alloy

FC. Electrode potential test (use of magnitude of electromotive force to determine composition of material or integrity of surface coating)

FC. . Surface contact cell

<u>Attributes measured or detected</u>

1. Porosity through electroplate or cladding
2. Surface inclusions

FD. Chemical spot tests (use of characteristic chemical reactions to identify specific elements)

FDA. Varied

<u>Attributes detected or measured</u>

1. Porosity through electroplate or cladding
2. Composition

APPENDIX B

BOOKS

Berger, H., NEUTRON RADIOGRAPHY, American Elsevier Publishing Co., New York, N.Y., 1965.

Betz, C. E., PRINCIPLES OF MAGNETIC PARTICLE TESTING, 1966.

Blitz, J., FUNDAMENTALS OF ULTRASONICS, Plenum Pub. Corp., New York, N.Y., 1963.

Carlin, B., ULTRASONICS (2nd ed.), McGraw-Hill Book Co., Inc., New York, N.Y., 1960.

Filipczynski, L., Pawlowski, Z., and Wehr, J., ULTRASONIC METHODS OF TESTING MATERIALS (translated by Schlaster and ed. by Blitz), Butterworth & Co., London, England, 1966.

Goldman, R., ULTRASONIC TECHNOLOGY, Reinhold Publishing Co., New York, N.Y.,

Halmshaw, R., PHYSICS OF INDUSTRIAL RADIOLOGY, American Elsevier Pub. Co., New York, N.Y., 1966.

Hogarth, C. A., and Blitz, J., TECHNIQUES ON NON-DESTRUCTIVE TESTING, Butterworth & Co., Ltd., London, England, 1960.

Hogarth, C. A., and Blitz, J., TECHNIQUES OF NON-DESTRUCTIVE TESTING, Plenum Publishing Corp., New York, N.Y., 1960.

Lamble, J. H., NON-DESTRUCTIVE TESTING, John Wiley & Sons, New York, N.Y., 1968.

McGonnagle, W. J., NONDESTRUCTIVE TESTING, McGraw-Hill Book Co., Inc., New York, N.Y., 1961.

McMaster, R. C., (editor), NONDESTRUCTIVE TESTING HANDBOOK, Ronald Press Co., New York, N.Y., 1959.

Rockley, J. C., AN INTRODUCTION TO INDUSTRIAL RADIOLOGY, Butterworth & Co., Ltd., London, England, 1964.

Stanford, E. G., Fearon, J. H., and McGonnagle, W. J. (Ed.), PROGRESS IN NON-DESTRUCTIVE TESTING (3 volumes), PROGRESS IN MATERIALS SCIENCE (2 volumes), The Macmillan Company, New York, N.Y.

NONDESTRUCTIVE TESTING IN NUCLEAR TECHNOLOGY (2 volumes), Proceedings of an International Symposium held by the International Atomic Energy Agency in Bucharest, 17-21 May 1965, IAEA, 1965.

PROCEEDINGS OF THE THIRD INTERNATIONAL CONFERENCE ON NONDESTRUCTIVE TESTING held in Tokyo and Osaka, March 1960, Pan-Pacific Press, Tokyo, Japan, 1961. 1-58 Minami-Sakumacho, Minato-Ku, Tokyo, Japan.

PROCEEDINGS OF THE FOURTH INTERNATIONAL CONFERENCE ON NON-DESTRUCTIVE TESTING, Butterworth & Co., Ltd., London, England, 1964.

PROCEEDINGS OF THE SYMPOSIA ON NONDESTRUCTIVE TESTING OF AIRCRAFT AND MISSILE COMPONENTS (5 volumes, 1961-67). Western Periodicals, North Hollywood, Calif.

SYMPOSIUM ON NONDESTRUCTIVE TESTING IN THE MISSILE INDUSTRY. STP. No. 278. American Society for Testing and Materials, Philadelphia, Pa., 1960.

SYMPOSIUM ON RECENT DEVELOPMENTS IN NONDESTRUCTIVE TESTING OF MISSILES AND ROCKETS. STP No. 350. American Society for Testing and Materials, Philadelphia, Pa., 1963.

APPENDIX C

Technical Periodicals and Abstract Journals and Services

Applied Materials Research
Applied Optics
Australian Journal of Nondestructive Testing (Australia)
British Journal of Non-Destructive Testing (U.K.)
Defektoskopiya (USSR) (Translated cover-to-cover as "Defectoscopy")
I E E E Transactions on Instruments and Measurements
I E E E Transactions on Nuclear Science
I E E E Transactions on Ultrasonic Engineering
Journal of the Acoustical Society of America
Journal of Applied Physics
Journal of Scientific Instruments (U.K.)
Materials Evaluation
Materialprufung (Germany)
Materials Research and Standards
Neutron Radiography Newsletter (Amer. Soc. Nondest. Test.)
Quality Assurance
Review of Scientific Instruments
Soviet Physics (Acoustics) (Translation of USSR Journal)
Transaction, American Nuclear Society
Ultrasonics (U.K.)
Ultrasound

Abstract Journals and Services

Applied Technology Index (titles only)
Chemical Abstracts
Current Contents (titles only)
Electrical Engineering Abstracts
Engineering Index
Info - NDT (U.K.) (titles only)
Metals Abstracts (U.S. and U.K.)
Nuclear Science Abstracts
Physics Abstracts
Reliability Abstracts and Technical Reviews
Scientific and Technical Aerospace Reports (STAR)
Technical Abstracts Bulletin

FOREIGN INFORMATION SOURCES ON NDE

AUSTRALIA

TESTING, INSTRUMENTS & CONTROLS, P. O. Box 250, North Sydney, N.S.W., Australia.

GERMANY

MATERIALPRUFUNG, VDI-Verlag GmbH, 4 Dusseldorf 1, Postfach 1139, West Germany

ABSTRACT SERVICE by the Deutsche Gesellschaft fur Zerstorungsfreie Prufverfahren e. V., 1 Berlin 33 (Dahlem), Ihnestrasse 52, Berlin - West.

GREAT BRITAIN

THE BRITISH JOURNAL OF NON-DESTRUCTIVE TESTING, The Non-Destructive Testing Society of Great Britain, Chalkwell Park House, 700 London Road, Westcliff-on-Sea, Essex, Great Britain.

NON-DESTRUCTIVE TESTING, Research and Practice, Iliffe Science and Technology Publications Ltd., 32 High Street, Guildford Surrey, Great Britain.

ULTRASONICS, Iliffe Science and Technology Publications Ltd., 32 High Street, Guildford Surrey, Great Britain.

THE QUALITY ENGINEER, Institute of Engineering Inspectors, 15 Cleveland Square, London W-2, England.

NDT INFO, Dorset House, Stamford St., London, S. E. 1, England.

JAPAN

JOURNAL OF N. D. I., The Japanese Society for Non-Destructive Inspection, 1-11, Kanda Sakumacho, Chiyoda-Ku, Tokyo, Japan.

U. S. S. R.

DEFECTOSCOPY, Consultants Bureau, 227 West 17th Street, New York, N. Y. 10011.

APPENDIX D

Literature and Information Sources for "New Phenomena"

HOLOGRAPHY AND COHERENT OPTICS

Journals of primary publication
- Applied Physics Letters
- Journal of the Optical Society of America
- Journal of the Acoustical Society of America
- Applied Physics

Most useful abstract journals
- Physics Abstracts
- Laser Abstracts
- Journal of Current Laser Abstracts

ULTRASONIC IMAGING--INCLUDING ACOUSTIC HOLOGRAPHY

Journals of primary publication
- Journal of the Acoustical Society of America
- Applied Physics Letters
- I E E E Transaction on Ultrasonic Engineering
- Materials Evaluation
- Applied Optics
- Journal of the Optical Society of America

Most useful abstract journal
- Physics Abstracts

MÖSSBAUER EFFECT

Journals of primary publication
- Physical Review Letters
- Physical Review
- Physics Letters

PULSED EDDY CURRENTS

Journals of primary publication
- Materials Evaluation
- Review of Scientific Instruments
- I E E E Transactions on Instruments and Measurements

Most useful abstract journals
- International Aerospace Abstracts
- Scientific and Technical Aerospace Reports
- Nuclear Science Abstracts

Electrical Engineering Abstracts
Physics Abstracts
Technical Abstracts Bulletin

POLYMER SCIENCE

Journals of primary publication
Journal of Polymer Science
Journal of Macromolecular Science
Macromolecules (new journal)

Most useful abstract journal
Chemical Abstracts

RHEOLOGY

Journals of primary publication
Transactions of the Rheological Society
Rheologica Acta

Most useful abstract journals
Rheology Abstracts
Applied Mechanics Review
Solid Rocket Structural Integrity Abstracts

ELECTRONIC MATERIALS (SEMICONDUCTORS AND SUPERCONDUCTORS)

Journals of primary publication
Journal of the Electrochemical Society
Journal of Applied Physics
Journal of the Physics and Chemistry of Solids

Most useful abstract journals
Chemical Abstracts
Solid State Abstracts

SIGNAL ANALYSIS

Journals of primary publication
Proceedings of the I E E E
I E E E Transactions on Information Theory
I E E E Transaction on Control Systems
I E E E Transactions on Systems Science and Cybernetics

Most useful abstract journals
U.S. Government Research and Development Reports
I E E E Spectrum

APPENDIX E

Information Centers

Centers devoted solely to nondestructive evaluation

Nondestructive Testing Information
Analysis Center
Army Materials and Mechanics Research
Center (Attn. AMXMR-TMT)
Watertown, Massachusetts 02172

The Nondestructive Testing Centre
Atomic Energy Research Establishment
Harwell, Didcot
Berkshire, England

General technical information centers

AEC-NASA Space Nuclear Propulsion Office
Atomic Energy Commision
Washington, D.C. 20545

Aerospace Materials Information Center
Mr. E. Dugger, AFML (MAAM)
Wright-Patterson Air Force Base, Ohio 45433

Aerospace Research Application Center
Indiana University Foundation
Bloomington, Indiana 47405

American Society for Testing and
Materials
1916 Race Street
Philadelpha, Pa. 19103

American Society for Quality Control, Inc.
161 West Wisconsin Avenue
Milwaukee, Wisconsin 53203

American Welding Society
345 East 47th Street
New York, N. Y. 10017

Ames Research Center
Mountain View, California 94035

Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60440

Atomic and Molecular Processes Information Center
P.O. Box Y, Bldg. 9201-2
Oak Ridge, Tennessee 37831

Atomic Energy Levels Program
214 South Building
National Bureau of Standards
Washington, D. C. 20234

Ballistic Missile Radiation Analysis
Center
The University of Michigan
Willow Run Laboratories
P.O. Box 618
Ann Arbor, Michigan 48107

Battelle Defense Information Analysis
Center
Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201

Center for Application of Science and
Technology
Wayne State University
Detroit, Michigan 48202

Chemical Abstracts Service
2540 Olentangy River Road
Columbus, Ohio 43201

Chemical Propulsion Information
Agency
Applied Physics Laboratory
Johns Hopkins University
8621 Georgia Avenue
Silver Spring, Maryland 20910

Chemical Thermodynamics Properties
Center
Texas A & M University
College Station, Texas 77843

Clearinghouse for Federal Scientific and
Technical Information
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Cobalt Information Center
Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201

Commissioner of Patents
U.S Patent Office
14th and E Streets, N.W.
Washington, D. C. 20231

Cryogenic Data Center
Cryogenic Data Compilation Unit
Boulder, Colorado 80302

Defense Ceramic Information Center
Dr. Winston H. Duckworth
Columbus Laboratories
Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201

Defense Documentation Center
Cameron Station
Alexandria, Virginia 22314

Defense Metals Information Center
Mr. Roger Runck
Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201

Division of Technical Information
Extension
U.S. Atomic Energy Commission
P.O. Box 62
Oak Ridge, Tennessee 37831

Documentation Service of the American
American Society for Metals
Metals Park, Ohio 44073

Electronic Component Reliability Center
Battelle Memorial Institute
Columbus, Ohio 43201

Electronic Properties Information Center
Hughes Aircraft Company (E 148)
Culver City, California 90232

Electronics Research Center
Cambridge, Massachusetts 02139

Engineering Societies Library
345 East 47th Street
New York, N. Y. 10017

Flight Research Center
Edwards, California 93523

Goddard Space Flight Center
Greenbelt, Maryland 20771

Information Research Center (IRC)
Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201

Infrared Information and Analysis
Center
University of Michigan
Institute of Science & Technology
Willow Run Laboratories
Box 618
Ann Arbor, Michigan 48104

Isotopes Information Center
Building 3047
P. O. Box X
Oak Ridge, Tennessee 37831

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103

Kennedy Space Center
Cocoa Beach, Florida 32899

Knowledge Availability Systems Center
University of Pittsburgh
Pittsburgh, Pennsylvania 15213

Langley Research Center
Hampton, Virginia 23365

Lawrence Radiation Laboratory
University of California
Box 808
Livermore, California 94551

Lewis Research Center
Cleveland, Ohio 44135

Manned Spacecraft Center
Houston, Texas 77058

Marshall Space Flight Center
Huntsville, Alabama 35812

National Materials Advisory Board
Division of Engineering
National Research Council
2101 Constitution Avenue
Washington, D. C. 20418

Mechanical Properties Data Center
Mr. Albert Belfour
Belfour Stulen, Inc.
13919 West Bay Shore Drive
Traverse City, Michigan 49684

Mossbauer Effect Data Group
1049 Camino Dos Rios
Thousand Oaks, California 91360

National Aeronautics & Space Administration
Scientific & Technical Information Center
Code US
Washington, D. C. 20546

National Bureau of Standards
Office of Technical Information
Washington, D. C. 20234

National Referral Center for Science
and Technology
The Library of Congress
Washington, D. C. 20540

New England Research Application Center
University of Connecticut
Storrs, Connecticut 06268

North Carolina Science and Technology
Research Center
P. O. Box 12285
Research Triangle Park
North Carolina 27709

Nuclear Fuels Technology Information Center
Oak Ridge National Laboratory
P. O. Box X
Oak Ridge, Tennessee 37830

Nuclear Safety Information Center
Oak Ridge National Laboratory
P. O. Box Y
Oak Ridge, Tennessee 37830

Plastics Technical Evaluation
Center (PLASTEC)
Picatinny Arsenal
Dover, New Jersey 07801

Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201

Radiation Shielding Information Center
P. O. Box X
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Redstone Scientific Information Center
C. G., U. S. Army Missile Command
Directorate of Res. and Development
Redstone Arsenal, Alabama 35809

Research Institute
University of Dayton
300 College Park
Dayton, Ohio 45409

Research Materials Information Center
Oak Ridge National Laboratory
P. O. Box X
Oak Ridge, Tennessee 37830

Science Information Exchange
Smithsonian Institution
1730 M Street, N. W. - Room 300
Washington, D. C. 20036

Shock & Vibration Information Center
U.S. Naval Research Laboratory
Code 4020
Washington, D. C. 20390

Stanford Linear Accelerator Center
Stanford University
P.O. Box 4349
Stanford, California 94305

Superintendent of Documents
U.S. Government Printing Office
Washington, D. C. 20402

Technology Application Center
University of New Mexico
P.O. Box 185
Albuquerque, New Mexico 87106

Technology Use Studies Center
Southeastern State College
Durant, Oklahoma 74701

Thermo Physical Properties Research Center
Dr. Y. S. Touloukian
Purdue University
2595 Yeager Road
West Lafayette, Indiana 47906

Transducer Information Center
Battelle Memorial Institute
Columbus, Ohio 43201

Western Research Applications Center
University of Southern California
Los Angeles, California 90007

SECTION IV

Technical Problem Areas

MEMBERSHIP OF THE PANEL

R. W. McClung, Chairman

R. B. Oliver

R. R. Rowand

FOREWORD

The enumeration and discussion of all details of all NDE problems facing the Department of Defense (DOD) would fill many volumes, would require far more time and effort than were available and, in the opinion of the Panel, would be beyond the proper scope of this report. For these reasons, it was necessary to select a plan of attack which could be most beneficial to all phases of NDE. In keeping with the original charge delivered by Mr. Nathan Promisel, Executive Director of the Materials Advisory Board, we set our sights toward long-range needs rather than short-term goals. These principles allowed us to bypass detailed consideration of specific hardware problems of current interest to DOD, since many of these were recognized in prior MAB activities, and should be pursued by DOD agencies and contractors without further identification. We elected to organize this section according to materials and processing problems, citing those problems which were the most universal and whose solution would offer the largest payoff to the greatest number of systems. This approach called attention not only to the materials evaluation problems but also to the needs for advanced NDE techniques and equipment. The Panel gratefully acknowledges the aid of the staff engineer, Mr. Kornhauser of the National Research Council, and the other members of the Committee for their helpful suggestions, evaluations, and criticisms of the drafts of this report.

CONTENTS

ABSTRACT

This Panel surveyed the reports of previous MAB committees and the inputs from the Army Materiel Command, the Navy, and The Technical Cooperative Program. These problem statements provided representative coverage of Department of Defense needs. The majority of the problems involved were well characterized and could be handled best by the proper use of nondestructive evaluation during the development and manufacture of the material and the processing of the product. These problems did not require advancing the state of the art as much as selecting test parameters, designing tooling, defining acceptance levels, and using more than one technique to evaluate a part or material. Their inclusion with problems requiring innovative development is indicative of the need for better communication between the experts in and the users of NDE services. Due to the limits of time and effort, the following general problem areas were selected--areas requiring extensive technique development or innovation:

1. Joining (mechanical fasteners, adhesive bonding, solid state welding, brazing and fusion welding)
2. Coatings
3. Composite materials
4. Graphites and ceramics
5. Alloy verification
6. Surface cleanliness
7. Residual stress
8. Fatigue
9. Thin materials
10. Corrosion and stress corrosion

Definition of the above problems and a summary of recommendations follow.

Joining: This group of five functionally-related problems is the objective for immediate study. (1) Fusion welding requires more quantitative techniques, lowering of the minimum detectable defect size, and imaginative new techniques of data acquisition and analysis. (2) The basic problem for adhesive

(chemical) and solid state (diffusion) welding is evaluation of bond strength for which innovative development will be needed. (3) Mechanical fastening and brazing appear to be problems of characterizing the specific joint design, tailoring existing techniques to the specific problems and, for certain configurations, innovations to allow evaluation in hidden locations.

Recommendations:

a. Conduct intensive development efforts on ultrasonic scatter detection methods, similar to the Delta Effect. Although conventional fusion weldments in steel and aluminum only need a detailed analysis of the specified requirements and of the economics of more exacting inspection, new NDE methods are necessary for welds of refractory materials and superalloys.

b. Pursue fundamental research in the physics of adherence as a prime objective in adhesive bonding, followed by the search for NDE methods that can be correlated with a parameter determining adhesive strength. Adhesive bond is a problem because of the need to know bond strength.

c. Determine ultrasonic transmission/reflection characteristics of various braze alloy/parent metal joints and correlate by destructive testing parameters measuring bond strength. Improve knowledge of the parameters produced in brazed bonds.

d. Study individually each configuration produced with mechanical fasteners since these problems are configuration-controlled.

Coatings: Advanced state-of-the-art methods are adequate for most coating problems, assuming careful characterization of the specific couple and configuration. Ingenious tooling and careful evaluation of limits for flaws are required for most coating problems.

Recommendations:

a. Develop extensively methods for detecting fine voids in sprayed metallic coatings. A promising approach appears to be the use of eddy currents created by a very high frequency and coils in the size range of 0.005 and 0.015 inches.

b. Create coating adherence evaluation techniques from the results of the research on physics of adherence (recommended under Joining) whose study is basic for all bond strength determination.

c. Define the accuracies and limitations of radiation back-scatter, thermo-electric, and eddy-current methods to analyze a wide variety of coatings/substrate couples for both coating thickness and alloy composition uniformity (chemical and microstructural variations).

Composites: Glass-resin composites have received considerable study, and current applicable NDE methods need more industrial application. The newer composites, such as metal/metal, metal/ceramic, and graphite resin have had relatively limited application of NDE in the determination of properties. In the development projects for new materials and components, funding should be provided to permit the concurrent evaluation of and correlation between the signals obtained by nondestructive techniques and the material condition producing the signals and the effect of these conditions on the materials properties.

Recommendations:

a. Increase the current effort in characterization of composites using the type of NDE methodology which has resulted in the reliable prediction of mechanical properties of interest to DOD designers.

b. Study the basic scientific phenomena to create NDE methods to ascertain quantitatively and qualitatively the characteristics of composites of metallic fiber/metallic matrix, metallic fiber/nonmetallic matrix, and nonmetallic fiber/nonmetallic matrix.

c. Develop techniques to apply microwaves to all nonmetallic composites in order to evaluate material characteristics and to detect flaws such as surface cracks, voids, and unbond.

d. Investigate frequency modulated ultrasound applied to highly attenuating composite materials as an evaluating technique for properties such as density, strength, and flaw detection.

Graphite and Ceramics: NDE techniques have been studied for a few nuclear and aerospace applications of bulk graphite. Laboratory work is well advanced for the detection of flaws in certain grades of materials and for the prediction of mechanical properties. Transition from laboratory techniques to industrial practice is needed. Generally, these materials are used in structures whose design precludes adequate evaluation after the installation of the graphite or ceramic component.

Recommendations:

a. Derive specification requirements during the experimental material and component development projects to establish process controls of the properties of these highly variable materials and to define qualitative and quantitative parameters.

b. Develop correlation between NDE data and service performance in structural applications.

c. Evolve methods to evaluate these materials after installation in an assembly and during service. Investigate frequency modulated ultrasound and acoustic emission as promising methods for detecting and monitoring cracks.

Alloy Verification: This problem has been ignored in spite of its importance and the availability of the necessary testing techniques. Alloys are specified for critical parts but rarely is any effort made to verify the alloy composition in the final part, although many opportunities exist for mixing of alloys.

Recommendations:

a. Enforce drawing requirements for alloy verification of finished parts.

b. Promote the development of a portable x-ray spectrograph, simultaneously reading test specimens and calibration samples, for rapid alloy verification.

Surface Cleanliness: Critical aerospace components frequently have stringent cleanliness requirements. Coating and bonding problems are dependent upon surface preparation, but our survey does not indicate the existence of objective, quantitative methods to evaluate surface cleanliness.

Recommendations:

a. Promote development of innovative methods, such as low energy electron reflections, to evaluate surface films and soils.

b. Sponsor studies for scanning techniques to evaluate surfaces for embedded, minute particles (as from grit blasting) which would degrade the bonding of coatings, etc.

Residual Stress: The magnitude and sign of the residual stress in a part are areas of uncertainty in stress analysis. The current methods have limited applicability. A concerted effort is needed to adapt potentially applicable NDE techniques to the specific residual stress problems.

Recommendations:

a. Continue studies to correlate ultrasonic velocity measurements in the various modes with residual stress.

b. Study the applicability of polarized eddy-current probes in orthogonal coil configurations for the determination of residual stress.

Fatigue: Evaluation of incipient fatigue or remaining fatigue life is a problem as old as the field of organized NDE. A concentrated interdisciplinary effort is required to identify precursors and to monitor fatigue progression.

Recommendations:

a. Identify precursors of fatigue cracks in terms of phenomena detectable by NDE techniques.

b. Study the chartability of the fatigue process using ultrasonic techniques to interrogate with two or more modes coupled with sophisticated data correlation methods.

Thin Materials: Instrument limitations have retarded application of NDE techniques to the evaluation of thin materials. Examples of needed apparatus development are: very high frequency eddy-current instruments, higher frequency and higher resolution ultrasonic instruments, and very low energy x-ray equipment.

Recommendations:

a. Conduct a survey to determine need and to define characteristics and limits for acceptance.

b. Assess the ability of available eddy-current equipment operating at 5 MHz and ultrasonic equipment operating at 25 MHz to meet the above requirements and develop improved equipment to meet the deficiencies.

Corrosion and Stress Corrosion: The state of the art is adequate for exposed surfaces, but no adequate approach exists for corrosion in blind areas or under protective coatings.

Recommendations:

a. Explore radiation back-scatter methods for the detection of corrosion products under protective coatings.

b. Study the applicability of ultrasonic scatter measurements, similar to the Delta Effect, coupled with data correlation techniques for the detection of such corrosion.

I. INTRODUCTION

Nondestructive evaluation methods have not reached their ultimate utility for several reasons. Advances in materials technology have created new classes of materials, new assembly techniques and new evaluation problems which have not been completely resolved. This section is intended to delineate those major problem areas in which current practice in nondestructive evaluation is inadequate and improvements are recommended. The needed improvements may be the development of new techniques and equipment or they may be the transition of information about existing methods and techniques from specialized laboratories to the production or maintenance facility with the problem. A major problem is defined as one of broad significance to materials' characterization or component inspection but which is not likely to be resolved within a couple of years with current efforts. The principal subdivisions in this section are oriented toward individual materials or processes with brief discussion of the nature of the testing problem. Although the material or process may be quite diverse or specialized, many of the test problems have common aspects. Some of the common problems will be mentioned in the introductory section to avoid undue repetition in the various subdivisions.

Many sources of reference were used in the compilation of this report. These include the NDE work by the Aerospace Manufacturing Techniques Panel [MAB-139-M (AAT-2)], the Aerospace Manufacturing Techniques Panel [MAB-200-M (AAR-3)], and the Committee on Aerospace Manufacturing Requirements [MAB-231, Vols. II and III]. Beneficial inputs were also provided by personnel from the Army Material Command, the Navy, the Air Force, the National Aeronautics and Space Administration, and the Technical Cooperative Program. Problem definition and evaluation were enhanced by the fact that individual panel members were also active participants in the aforementioned MAB Aerospace Committee, the Defense Conference on Nondestructive Testing, the AEC-Nondestructive Testing Working Group, and comparable aerospace nondestructive evaluation committees.

While there are some good research and development programs being performed on methods, techniques, and apparatus, increased attention should be given to achieve efficient transition from the laboratory stages to production or maintenance application. There must be better communications, liaison, and feedback between management, production designers, fabricators, users, and nondestructive evaluation personnel so that pertinent problems can receive necessary recognition and attention. For example, on materials with little background testing history, better definition is needed of the properties to be measured--is it density, modulus, porosity, and/or some other series of attributes? The materials engineers need to determine the necessary quality levels by which the nondestructive evaluation engineer can establish the evaluation method. Only by common agreement can intelligent advances be made in testing technology.

Recognition must be given to the necessity for tailoring nondestructive evaluation to the specific problem. More than one test method may be required. The test situation has become a problem because single, generalized methods are inadequate. The factors which must be considered in the design of an inspection method include the material, configuration, size, characteristic properties, reference standards, cost (both of the part and the examination), and the consequences of failure.

Nondestructive test development and application should begin at the same time as the development on new materials. By such concurrent development, with associated feedback of information to the processor, necessary adjustments can be made in the fabrication stages to assure better products at lower costs. Another major benefit of early development of NDE is the establishment of firm correlations between the signals obtained during an inspection, the material conditions producing the signals, and the effect of the conditions on the material performance in service. If NDE information is not gathered and rapidly disseminated to all involved parties, the final inspection of fabricated parts can be no better than a station for rejection of questionable parts on the basis of uncertain criteria. Use of NDE as a part of

final inspection is necessary and desirable, but is a small fraction of its potential capabilities.

Most nondestructive evaluation in the past has been primarily qualitative in nature. Significant benefits will be realized by increasing emphasis on the quantitative aspects--how large is the discontinuity (a necessity for Fracture Mechanics)? Where is the flaw? What is the density, depth, type, etc. ? To provide meaningful support as a quality control tool toward improvements in material processing, the capabilities of nondestructive evaluation methods must be developed so that minor variations in the material attributes may be evaluated. Only with quantitative measurements can the results of minor processing changes be assessed and used to select optimum methods. Realization of this goal will be difficult, requiring extensive development effort.

No attempt has been made to define or discuss the ultimate limits of sensitivity or "how small a flaw can be detected in material." The many variations of methods, techniques within methods, materials, conditions of materials, and specimen configurations make such attempts impractical and useless. The question should not be "how small a flaw can be found?" but rather what size and characteristic of flaw will be detrimental to the service of the component and how well can NDE measure the flaw or other condition of interest in terms of its significance? The latter philosophy has been the guideline in developing this section.

Improved methods are needed for processing the voluminous data generated by nondestructive testing instrumentation. Automatic processing of data again emphasizes the need for quantitative output from the test. The returns for such capability are tremendous, including: (1) more rapid feedback during material processing for process control; (2) utilization of more of the data (much of which is currently ignored because of lack of time or ability for interpretation); (3) comparison of data from the same material at varying intervals to evaluate changes which may be occurring during service (fatigue, metallurgical changes, changes in stress level, corrosion, etc.).

The aforementioned needs for the advancement of nondestructive evaluation are applicable to most of the test methods and should be kept in mind as hardware-oriented problems are described.

The problems are listed in a priority sequence established according to the universality of the need, the recognition of practical approaches, and accordingly, the likelihood of successful solution. The Committee recognizes that to any individual, organization, or department the most important and significant problem is that one which is currently being faced.

II. DISCUSSION OF PROBLEMS

1. Materials Joining

Many joining methods are used to couple individual components or units into assemblies or subassemblies of various sizes and intricate configurations. Generally these assemblies can be fabricated only by joining techniques. These include mechanical fastening, adhesive bonding, solid state welding, brazing, and fusion welding. These processes create many joint problems involving material strength, toughness, and fatigue strength. These problems are the result of the single or multiple interaction of various factors such as lack of fusion, porosity, precipitations, pickup of interstitial elements, distortion and cracking from induced stresses, fit up, unbond, edge distance of holes, and thermal stability of polymer adhesives. Assurance is needed that the joint is sufficiently flaw-free and has the necessary strength to provide the desired structural integrity.

Fusion Welding

Problem Definition. Thirty years ago fusion welding was not considered an acceptable joining process for critical applications without radiographic inspection for acceptance. Currently, the fusion welding practitioners and the fracture mechanics people are protesting that the available nondestructive evaluation techniques are inadequate for evaluation of critical weldments. The contradictory dilemma probably stems from the evolution of design demands. These demands have frequently outstripped the development of materials and are usually evidenced by very small safety margins (though, in fact, the small safety margins are generally relieved by conservatism in the design assumptions) which force the materials and

process engineers to sacrifice ductility for strength. The use of materials with low ductility, in turn, has led to a heavy emphasis on critical defect size and to a drastic decrease in the size of allowable discontinuities. Obversely, numerous published papers show that, with reasonable ductility, a high frequency of small discontinuities does not have a significant effect on the joint performance.

Current Approaches. Radiographic inspection has improved significantly in terms of both sensitivity and resolution and is far more usable under adverse field conditions. However, radiography is still limited on minimum detectable defect size, and defect orientation is still a critical problem unless several exposures are made for each increment of fusion weld seam.

Ultrasonic inspection has been used successfully and profitably for steel and aluminum fusion weldments, but the application to inspection for fusion weld joints in high performance (super) alloys has not been established. Complicating factors are that ultrasonic inspection of fusion welds requires skills and experience that are not always developed in the average organization. Further, the acoustical mismatch at the fusion weld/parent metal interface frequently results in loss of flaw signal or causes confusing, spurious signals. Lastly, those who demand an unusual quality requirement do not define and justify the exceptional requirement and fail to supply the financial resources and time needed to develop the techniques and skills to perform the exceptional task.

The attributes of interest that affect weld performance and which may be distributed throughout the volume of the fusion weld zone are: porosity (spherical, elongated, aligned), lack of penetration, lack of fusion, shrinkage, and cracks in any orientation. Also, in stringer welding, interpass lack of fusion is encountered. Integrity of the parent material can be a problem. The frequency and time of inspection is determined by a trade-off of the inspection cost and the cost of repairs.

While surface limited methods such as penetrant and magnetic particle inspection are available, only penetrating radiation (x ray and gamma ray) techniques and ultrasonic techniques show any promise to evaluate the total weld volume.

Acoustic emission and acoustic signature techniques have been used to functionally evaluate weld joint performance but these methods do not constitute an inspection.

Recommendations. The art-of-welding processes do not permit consistent production of perfect fusion welds, and past improvements of the state of the art of nondestructive evaluation of fusion welds do not promise rapid advances. These two facts indicate that the engineer must design within the limitations of materials and processes and that the nondestructive evaluation personnel must be brought into the development in time to evolve specific techniques and concurrently guide the fusion welding process improvement. Effort also should be made to match the requirements for inspection facilities and inspection training to the specification criteria.

Development is needed on penetrating radiation and ultrasonic techniques for the detection of smaller flaws. These development efforts apparently should be directed toward better detection and processing of signals. Radiography is limited by the film emulsion graininess and the physiological limitations of the human eye. One promising approach would be the use of a flying-spot scanner with computer data processing/autocorrelation technique to scan the x-ray film. The spot could be made sufficiently small to detect images on the film that are beyond the capability of the best trained human eye. This approach presupposes continued improvement in x-ray recording media. A fine, flying-spot direct x-ray beam scan would be desirable for certain applications but appears to be beyond the predictable state of the art.

Ultrasonics, as currently used, will require widespread application of conventional techniques on conventional materials to develop inspectors of only average competence. Additional research is badly needed to uncover unexploited ways to use ultrasonic waves which can propagate in numerous modes. Techniques utilizing scatter from interfaces rather than the directly reflected beam have been explored with considerable promise; this approach should be diligently pursued. Techniques related to ultrasonic holography have intriguing possibilities and further exploration

is recommended. New data acquisition and processing techniques should be explored for their potential application to ultrasonic inspection.

Adhesive Bonding

Chemical adhesives constitute another major joining method. Development of new materials in recent years has resulted in joints with sufficient strength to be used for many applications. The principal requirement for such joints is that the bond have adequate strength to withstand the loads. The tests must be performed both during processing as well as following fabrication. For some applications, it may be desirable (or even mandatory) that re-evaluation be performed at intervals during service. Among the principal test methods currently being used are mechanical vibration (sonic or ultrasonic), radiography, and thermal (infrared) radiation.

Improved methods are needed for the measurement of both cohesive and adhesive strength. As precursors, it will be necessary to develop improved understanding of adhesion and cohesion as related to the strength of chemical bonds. The importance of achieving and measuring surface cleanliness for bonds will be discussed further in the subsection on Surface Cleanliness.

Mechanical Fasteners

Mechanical fastening is perhaps the oldest method of joining materials and includes such things as the use of screws, nuts and bolts, and rivets. The principal problems for critical applications are ascertaining whether undue stress or localized failure has occurred because of improper use. This could include evaluation both at assembly and, depending upon the consequences of failure, at intervals during service. Because of the very large number of such fastenings, the inspection cost per joint must be kept low. Consequently, little more than visual or manual examination is currently practical. New areas of development should be explored to measure the stress, minimal distortion, or some other meaningful attribute characteristic of a proper fastening.

Solid State Welding

In solid state welding processes, such as roll welding, explosion welding, and diffusion welding, metallurgical bonds can be developed without melting the parent metals and without the addition of foreign materials. As with other welding techniques, the principal problems are detection of areas of unbond and measurement of strength of welded areas. Ultrasonic and infrared techniques have been used successfully in certain cases to detect unbond but with little success on the measurement of weld strength. In solid state weldments, a better understanding is needed of the mechanisms producing the metallurgical bond so that meaningful evaluations may be made of the proper parameters. New methods are needed for measuring the changes in compositional gradient produced during diffusion.

Brazing

Brazing has testing problems including detection of unbond, measurement of strength and, under certain conditions, changes in chemical composition due to diffusion or dilution. Radiographic techniques have been applied to the detection of voids in brazed joints and ultrasonic techniques have been applied to the detection of voids and unbond. Again, measurement of strength is a significant problem needing attention. As brazing techniques are applied to nonmetals advances in the more conventional methods may be necessary to achieve useful results.

2. Coatings

Problem Definition

Examination methods are needed to evaluate coatings for integrity, thickness, and bond quality. The use of one material coated upon another as a protective layer is an ancient process, but modern materials technology has generated many new needs and materials for coating. This, in turn, has multiplied the testing problems. The coatings are applied for a variety of reasons including protection from the atmospheric environment (e.g., paint, plating, etc.), protection at high temperatures (ceramics), protection from excessive wear (bearing surfaces), and many others. The coating may be organic, inorganic, ceramic, or

metallic, depending upon the properties desired. The mode of application includes liquid dipping, painting, reaction with an environment (anodizing or case-hardening), flame or plasma spraying, and vapor, electrical, or chemical deposition.

After the desired coating material has been applied, assurance must be provided that the design results have been achieved. Many of the attributes which need interrogation are similar despite the wide diversity of materials, applications, and missions. The first burden rests upon the designer or user to establish the desired quality levels and determine the probable cause and consequence of failure. For instance, the selection of a test method and establishment of test techniques and sensitivity for the detection of flaws including chemical and microstructural variations in the coating will vary markedly between the requirement to detect microscopic pinholes and the assurance that no gross flaws occur. Measurement of coating thickness on materials exhibiting a gradual transition in composition from substrate to coating will be more difficult because of the lack of a well-defined interface. Determination of quality of the bond is a significant problem with many facets which are discussed in the subsection on Materials Joining.

Time and Frequency of Inspection

Tests should be performed during or soon after the application of the coating to allow feedback of data for process control. If there is concern over degradation of the coating, re-evaluation after service must be performed.

Current Approaches

Depending upon the combination of materials, coating thickness measurements have been performed by approaches such as magnetic methods, eddy-current techniques, radiation and scattering methods. Coating flaws have been detected by techniques such as liquid penetrants, electrified particles, electrical continuity and electrode potential techniques. The principal approach for bond quality has been the use of ultrasonics.

Recommendations

Improvements are needed on the existing techniques in accordance with the Introduction to the Problem Areas including more quantitative results and correlation with service performance. Better definition and measurement of properties are needed for the evaluation of bond quality. Further work is needed for the detection of microscopic flaws when they are deemed detrimental.

3. Composite Materials

Problem Definition

Composite materials because of their multiple component structure continue to present a significant challenge to nondestructive evaluation technology for the detection of flaws and measurement of basic attributes. Composite materials may be defined as those materials that consist of two or more distinct materials combined to produce a structure that may surpass many of the physical, chemical, and mechanical properties of homogeneous materials when used singly. This discussion also includes honeycomb and sandwich structures as composites. The fact that a composite is composed of several materials combined in a unique fashion hinders the application of many conventional nondestructive tests. Despite technical hurdles, some nondestructive testing techniques have been developed and effectively applied to composite inspection. Discussion of nondestructive evaluation for composites must consider three areas: in-service, the broad spectrum of manufacturing or production control, and materials research activities.

Honeycomb and Sandwich Construction

Metal and plastic honeycomb and sandwich composite structures may receive nondestructive evaluation for entrapped water, crushed core, and unbond. Radiographic, ultrasonic, infrared, eddy-current, penetrant, and optical techniques are the methods generally used for in-service inspection. O of the most reliable methods to detect unbond is still the coin-tap test, but unfortunately it is only qualitative in nature. Recently, a new technique of generating sonic vibrations by electromagnetic methods has been adopted for inspecting metal honeycomb.

However, the application of nondestructive evaluation technology to plastic composite structures still lags behind the development of structures and structural materials. This is largely the result of the extremely limited work pursuing correlation of nondestructive evaluation technology with composite material problems.

Boron/Resin Composites

The development of nondestructive evaluation techniques for boron/resin composites has been accomplished concurrently with their evolution. Conventional methods (radiography, ultrasonics, infrared, et al.) are currently being evaluated to determine their limits of resolution and sensitivity for detecting various discontinuities. Advanced composites are now being applied to experimental parts on a number of aircraft to demonstrate their feasibility as structural materials. However, because of the low accumulated test time and the apparently limited consideration of nondestructive evaluation in test planning, many of these structures have not been inspected nondestructively to a satisfactory extent.

Current Approaches

Research to improve the capability to inspect composites is continuing. Techniques such as high-resolution ultrasonics, microradiography, and gamma radiometry are being optimized for the determination of fiber alignment and continuity, void content, and unbond. Liquid crystals, by their ability to change color with temperature, can be used to detect delamination in certain composites. A thermal method using an infrared detector has been developed to identify unbond conditions in honeycomb panels. Among other useful techniques, gamma radiometry has been successfully applied to the characterization of plastic composite panels by its use in the detection of component volume percentages. Techniques such as holography and x-ray tomography are also being studied for possible application on composites. Nondestructive evaluation techniques are also being developed for metal-matrix composites and must now keep pace with the development of three-dimensional resin-matrix composites. Some work has been done

on nondestructive methods for determination or prediction of composite materials properties. For example, a relatively new technique using ultrasonic velocity measurement has been successful in determining the flexural and tensile moduli of E-glass plastic laminates.

Progress is being made in the application of nondestructive evaluation to in-service use and manufacturing of composites, but research to provide better methods is limited. A number of new methods do show promise. However, one of the limiting factors is the inability to convince designers and fabricators of the value of nondestructive evaluation.

Recommendations

Among the areas where emphasis should be placed in manufacturing are: (1) inspection of fibers and tape prior to their incorporation into matrices, and (2) nondestructive evaluation methods for determining deviations in the manufacturing process which may then be corrected by automatic feedback systems.

New methods and systems must be developed to fill the needs for nondestructive testing facilities in manufacturing processes. For example, little if any work has been done to devise nondestructive testing techniques for evaluating the quality of bonds for joining composites to each other, or to other materials. Development of inspection techniques for adhesive bond strength would greatly increase designers' use of composites.

4. Graphite and Ceramics

Problem Definition

Although intrinsically different materials, graphite and ceramics share, from both a nondestructive evaluation and materials point of view, a certain commonality. The rapid growth of these groups of materials as practical engineering structures has arisen from the increasingly stringent requirements for thermal protection, stability, and reliability.

Until recently, the only nondestructive evaluation developments were largely restricted to gross flaw detection and limited dynamic property measurements for idealized laboratory and production samples. Now, the ultimate goal for nondestructive evaluation applied to ceramics and graphite is assurance of material reliability. Although the applications are growing rapidly, nondestructive evaluation is currently used only where dictated in the production of costly "cannot fail" devices. The factors which are relevant to the ultimate behavior of these classically brittle materials may be divided into three divisions, which play a role in material performance:

1. Discontinuities
   a. Macro-defects-- } voids, porosity, cracks, striations,
   b. Micro-defects-- } inclusions, etc.
2. Properties--tensile strength, modulus, density, transport, etc.
3. Variability--nonuniformity within a component and between like components, e.g., density, anisotropy, etc. (variations)

<u>Current Approaches and Recommendations</u>

The primary techniques now available include thermal, x- and gamma-radiation, acoustic and chemical methods. While greater sensitivity is desired for the measurement of the factors listed above, perhaps more urgent is the need to use available technology at all stages of production from material synthesis to finished product. As stated earlier, this allows establishment of standardized tests and correlation to service life.

Unfortunately, it is quite difficult to predict the influence that variability, discontinuities or property deviations will exert on material performance and reliability. Therefore, efforts should be initiated to determine the significance of factors related to service and performance.

5. Alloy Identification and Sorting

Problem Definition

Improved methods are needed to assure the identity of alloys. In the steps between the melting furnace and the finished product, there are many opportunities for inadvertent mixing or loss of identification of alloys. Where the alloys are carefully selected, matching properties and characteristics to the design requirements, it is imperative to verify that the product is made of the specified alloy. There are also economic and contractual reasons for development of more definitive alloy identification methods and increased use of the methods.

With few exceptions, the wide variety of diverse and special alloys cannot be identified with the simple human senses. The only true identification of an alloy is through complete chemical analysis, but this is time-consuming, expensive, and generally, destructive. There are numerous measurements that can be correlated with composition, but most are affected by both the spread of composition (from two to twenty elements) and the prior mechanical and thermal history so that there will be statistical spread of data for any given alloy. If a small number of alloys are to be separated and if there is a large difference between their nominal or mean value, one method could suffice. As the number of alloys increase, so does their similarity; the overlap of data from any single nondestructive method causes ambiguity of identification requiring more methods to give a unique identification.

Current Approaches

The following are methods that have been used singularly with some degree of success:

1. Eddy currents
2. Thermoelectric potential
3. Electrochemical potential
4. Triboelectric effect or frictional EMF

5. X-ray fluorescent spectroscopy
6. Optical emission spectroscopy
7. Magnetic analysis

The combined use of two independent methods is generally many times more effective than either method used alone.

Eddy-current techniques have been widely used for alloy sorting, but they are markedly affected by prior mechanical and thermal history. They are limited to surface or near surface examination, and differences in specimen size and shape require a variety of coil configurations.

Thermoelectric potential methods have had limited application, and the method has the advantage that the readings are not greatly affected by the sample size and shape or prior thermal and mechanical history.

The electrochemical potential method shows promise as a sorting method and may have particular merit as a functional test to identify corrosion-resisting alloys. The literature shows very little data on this method. Surface preparation is required to ensure that the reading represents the base material and not some surface film.

The triboelectric or frictional EMF techniques have had only limited application, and the data indicate that the method has only limited potential.

X-ray fluorescent spectroscopy has great potential since it can quantitatively determine the major elements in an alloy. The method is limited by the size of the instrument, electric power requirements, radiation hazard, and by sample size requirements. Self-shielding of the heavier elements in the alloy will pose a complex problem for the development of calibration standards.

Optical emission spectroscopy is limited by sample size requirements, and it is not a satisfactory method for the major elements of an alloy. Spark or arc excitation of the spectrum leaves a burned spot on the part so the method is not truly nondestructive. Laser excitation should be considered, but a portable instrument poses several severe design and safety problems.

Recommendations

A portable x-ray fluorescent spectrograph capable of simultaneous determination of all major elements in the population of alloys would be the most direct single approach. A major problem is generation of a simple set of calibration standards.

The more promising approach is to use two or more methods that are independent in their response to composition changes and to differences resulting from prior thermal and mechanical history. Optimally, the two methods would be joined in one probe and instrument assembly with a combined, two-dimensional read-out (e.g., X-Y plotter). Current experience indicates that a third interrogation will be needed if the data for two alloys overlap for both methods.

6. Surface Cleanliness

Problem Definition

The success of many of the bonding processes is totally dependent upon the surface preparation. Historically, little attention has been paid to inspecting the prepared surfaces to insure adequate and controlled surface preparation prior to coating or bonding.

Strength and reliability requirements for bonded joints will become more demanding and will be met only if nondestructive evaluation techniques

are developed to measure surface cleanliness. Since there is no foreseeable method to nondestructively measure bond strength, we can profitably invest in test and inspection methods to control the cleaning process prior to bonding.

Current Approaches

The following are methods used by those industries producing high precision rotation machinery:

1. Indium adhesion
2. Solvent purity
3. Evaporation of carbon-14 labeled solvents
4. Goniometer-droplet contact angle
5. Light-scatter photometry
6. Replica transfer
7. Water break
8. Wipe test
9. Ultraviolet fluorescent scan.

These methods vary widely in sophistication and applicability. Generally, they are aimed at detecting films of grease-like materials and, with the exception of the water-break test and the ultraviolet fluorescent scanning, they only inspect a small sample of the surface. In this category, the indium adhesion test inspects only a pinpoint area, but it does measure the adhesive strength of the indium needle at that point, referenced to its adhesive strength on the surface of freshly cleaved mica. This particular test deserves attention since it can serve as a primary standard for method development and calibration.

Recommendations

Method development must be addressed at the problem of total inspection of large areas. The methods must detect and evaluate foreign films (grease, oil, wax, moisture, oxide), particulate matter (dust, lint) and embedded foreign materials.

Several methods for surface evaluation of nonviable soils involve coherent or noncoherent light reflection or scatter from the surface, scanning with low energy particles (alpha or beta in the 0.5 to 10 volt range), transient surface heating with infrared scanning and ultrasonic energy loss. Ultraviolet, visible or infrared illumination could be used, either polarized or not, and from either coherent or noncoherent sources. For some soil/surface combinations, scanning at Brewster's angle has promise. Also, some modifications of the Ulbricht Sphere may provide a tool to detect and evaluate low level scattered light.

For some soil/surface couples a transient heating of the surface followed by a high sensitivity infrared scan may reveal films of low heat conductivity or with a high emissivity differential.

Thin films on metallic substrates can be effectively detected and studied with very low energy beta or alpha particles, in the range from a fraction of a volt to 10 volts. Scatter from the film predominates in the lower end of the range while attenuation of the backscatter from the substrate predominates in the higher end of the energy range.

High-sensitivity ultrasonic Lamb wave or shear wave techniques have promise for the detection of nonwater wettable films on dense substrates. The detection is based on the differential in phase or impedance between filmed and nonfilmed areas.

7. Residual or Applied Stress

Problem Definition

Generally, conventional nondestructive evaluation methods are applied to assure that injurious flaws are not present to significantly affect the ability of a structure to withstand the anticipated operating stresses. However, a portion of the total stress on the component may be residual stress within the material, caused during one or more of the manufacturing stages or resulting from overstress or overstrain during service. This residual stress may change the strength of the material so that the nominal mechanical properties are no longer indicative

of a structure's ability to withstand an external stress without distortion and/or failure. Thus, designing must be conservative to allow for potential residual stresses. On the other hand, residual stresses can be used to advantage to enhance certain mechanical properties of materials where anticipated operating stresses are known. Examples of the latter include the prestressing in compression of concrete, glass, or other brittle materials to increase their ability to withstand tensile stresses in service. From the foregoing, obviously, the ability to measure the direction and magnitude of both residual and applied stresses within a material could increase confidence in the design, decrease the necessary safety factor, and give improved guidelines for allowable operating loads.

Time for Inspection

The proper occasion for measurement of internal stress will vary according to the material, configuration, and application, but could include some of the following:

1. Measurement during processing.
   a. If subsequent processing could be tailored to remove, reduce, or modify the stress (e.g., as in heat treatment of a metallic structure).
   b. If the component is vital to the load-bearing capabilities of the structure and subsequent assembly will render the component inaccessible.
2. Measurement after completion of fabrication.
3. Measurement after stages of operation to assure that distortion or other changes during service have not introduced unknown stresses.
4. Measurement during operation for confirmation of the anticipated service loads.

Current Approaches

A number of methods have been studied with varying degrees of limited success. The most widely applied techniques are indirect measurement of the stress-induced surface strain using such methods as strain gages, photoelastic materials, and brittle coatings. Of course, these methods are primarily applicable to the measurement of the resultant strain and provide little, if any, information on the residual stress. Work on the latter includes the use of x-ray diffraction to measure changes in the crystal lattice spacing of the material, the rotation of polarity of an ultrasonic shear wave, changes in the propagation of ultrasonic surface waves and, with transparent materials, changes in the optical properties.

Recommendations

Increased attention should be given to the development of improved quantitative techniques and equipment for field application. Apparently, ultrasonic techniques offer the greatest promise for internal volumes while ultrasonics, x-ray diffraction, or other methods may be candidates for surface measurements of residual or applied stress.

8. Fatigue

Problem Definition

Cyclic loading of structural members occasionally results in changes of properties, leading to localized progressive cracking commonly called fatigue. Early detection of the beginning of incipient fatigue or even the beginning of cracking could prevent the high cost of fatigue failure.

By the very nature of fatigue, little can be done to detect it prior to service. However, improved knowledge is needed on precursors which may lead to fatigue. Appropriate characterizing techniques should be developed to allow detection of the precursors. In addition, better cognizance of the operating characteristics of a component should allow improvement in design minimizing the problem of fatigue. Vital components whose failure would be expensive from any standpoint should receive periodic examinations at critical stress points to detect precursors, the beginning of fatigue or to check on the progress of any allowable fatigue.

Current Approaches

After a crack has formed, most of the conventional nondestructive evaluation techniques for surface crack detection are applicable. Some work has been performed on techniques to detect fatigue before actual crack formation. These include acoustic emission, ultrasonic surface waves, ultrasonic attenuation, eddy-current resistivity measurements, and holography. Most of this work has been in laboratories on simple fatigue specimens.

Recommendations

Continued work is necessary to improve ultrasonic, eddy current, optical, or other methods for the early quantitative detection of possible precursors or impending fatigue cracks and for the subsequent development of equipment for application to complex structures in situ. For examination after actual crack formation and before reaching the rejectable condition, existing techniques must be made more quantitative. If the intervals of inspection between operating periods are infrequent, capabilities need to be developed for evaluation during actual operation of the component.

9. Thin Materials

Problem Definition

Because of weight or physical clearance problems and for many specialized applications, it occasionally becomes necessary to employ very thin sections of materials. From the inspection viewpoint, "thin" may be defined as the thickness below which standard techniques are inapplicable or less sensitive due to film graininess, ultrasonic wave length, probe size, or other limiting factor. There must be assurance that the thin material has adequate integrity. However, as materials become thin, the size of the significant flaw also becomes smaller. This creates evaluation problems. Although many test methods normally define sensitivity in terms of a percent of specimen thickness (as in radiography), there normally is a minimum limitation imposed by some aspect of the test such as graininess of the radiographic film, the ultrasonic wave length, or size of the search probe.

For thin materials, the normally assumed minimum detectable flaw size may be excessively large.

Current Approaches and Recommendations

Improved examination methods for thin materials are needed during and after processing, and after service. Special techniques of most of the commonly accepted methods have been applied to thin materials including low-voltage radiographic techniques, x-ray sensitive television systems, high-frequency and Lamb-wave ultrasonics, high-frequency eddy currents and others. Most of these have been laboratory tests and transition is needed to allow more application under industrial or field service conditions. This will include both improved techniques and instrumentation.

10. Corrosion and Stress Corrosion

Problem Definition

Even after materials and components are adequately designed, fabricated, inspected, and installed, environmental conditions can cause corrosion or stress corrosion on portions of the hardware system, reducing its ability to perform satisfactorily. When the corrosion attack occurs in accessible areas, it can generally be detected visually or by other more sophisticated techniques which are currently available. However, when the corrosion is hidden (e.g., around fasteners, under coatings, or between contiguous components), detection and evaluation are much greater problems. Normally a moderate amount of corrosion can be tolerated, but gross corrosion and onset of cracking become more serious and detection is a necessity.

Current Approaches and Recommendations

Radiographic, ultrasonic, and eddy-current techniques have been used with varying degrees of success for the detection of corrosion. Since NDE techniques need to be applied on items in the field at intervals during service, the equipment should be extremely portable and versatile for application to a variety of configurations. More investigation should be made into factors contributing to stress

corrosion. Better correlation is needed between the NDE results and the severity of corrosive attack.

III. RECOMMENDATIONS

The recommendations are divided into two subsections: the first deals with general improvements in the performance, use, and administration of nondestructive evaluation methods which are applicable to all testing problems; the second deals with potential solutions to specific materials and processing problems.

General Recommendations

1. Improve communications and information exchange between product designers, basic material producers, fabricators, users, and nondestructive evaluation personnel for better delineation of materials and testing problems and to assure incorporation of nondestructive evaluation at the earliest possible stages and at other critical times in material and product development and in production.

2. Make nondestructive evaluation methods more quantitative and reproducible in terms of the material characteristic being evaluated.

3. Improve data processing.

4. Develop techniques for in-service inspection of systems.

5. Investigate new approaches or methods in addition to the above improvements to existing methods.

6. Improve transition of laboratory techniques to field or production application.

7. Establish a DOD Center of excellence for NDE, with the capability of conducting both long-range research and applied development, as the best method for implementing most of these recommendations for DOD problems.

Specific Recommendations

1. Materials Joining. Assurance is needed that joints are free of harmful defects and have adequate strength.

    a. Fusion Welding. Improve the information gathering and processing for both ultrasonic and radiographic techniques. Areas needing attention include:

        (1) Electronic scanning of x-ray film and computer processing of the data;

        (2) Development of new methods for superalloy and refractory alloy fusion weldments;

        (3) Use of ultrasonic scattering for flaw detection; and

        (4) Ultrasonic holography.

    b. Adhesive Bonding.

        (1) Initiate basic studies to develop improved understanding of adhesion and cohesion as related to bond strength.

        (2) Use new approaches for measurement of both cohesive and adhesive strength. No specific recommendations are offered but the section on Special Phenomena should be noted.

        (3) Develop improved methods of achieving and measuring surface cleanliness.

    c. Mechanical Fasteners.

        (1) Develop rapid stress or strain measurement techniques to monitor proper fastening.

        (2) Evolve techniques to detect cracks that may be hidden by fasteners.

    d. Solid State Welding.

        (1) Study the mechanisms producing strength in such solid state welds.

(2) Develop techniques for measuring compositional gradients produced by diffusion.

d. Brazing.

(1) Study the mechanisms producing strength.

(2) Improve conventional NDE techniques applicable to joints in which a nonmetal is joined to a metal or another nonmetal.

2. Coatings. Improved techniques are needed for measurement or evaluation of thickness, bond, and integrity of the coating.

a. Develop improved correlation between inspection data and mechanical and physical properties and service performance.

b. Make existing techniques such as radiation backscatter, thermoelectric, eddy currents, and ultrasonics more quantitative and reproducible. Applicability to various material combinations should be established.

c. Create very high frequency eddy currents and miniature coil systems for detection of small voids and chemical and microstructural variations in metallic coatings.

3. Composites. Nondestructive evaluation techniques are needed for the detection of flaws and the measurement of key attributes of composite materials. A major need is the increased utilization by industry of techniques now available in the laboratory.

a. Develop improved correlation between inspection data and mechanical and physical properties and service performance.

b. Evolve techniques for the evaluation of fibers and tape prior to composite fabrication.

c. Use nondestructive evaluation as a process control to detect manufacturing deviations.

d. Develop and apply advanced microwave techniques to nonmetallic composites.

e. Investigate frequency modulated ultrasound as a potential method for composite evaluation.

f. Study the ability of NDE methods for characterization of new metal-fiber and metal-matrix composites.

4. Graphite and Ceramics. Many of the NDE techniques normally used for metals are inapplicable on graphite or ceramics. The frequently encountered properties of inhomogeneity, anisotropy, and brittleness increase the interest in measuring the material attributes as they affect service performance.

   a. Improve characterization of materials by nondestructive evaluation as an aid to process control.

   b. Establish specification requirements for process control and quality requirements.

   c. Conduct correlation work to establish the relationships between nondestructive test data and material performance in service.

   d. Improve existing NDE techniques to provide more sensitive, quantitative results.

5. Alloy Identification and Sorting. Alloys are frequently specified for critical applications but, despite the ease with which mixing or loss of identification of alloys can occur, little is done to verify alloy composition.

   a. Develop equipment combining two or more test methods with independent response to compositional changes (e.g., eddy-current and thermoelectric).

   b. Develop a light-weight portable x-ray fluorescent spectrograph and a simple set of calibration standards.

   c. Conduct investigations toward development of practical tests using electrochemical potential or optical emission methods.

   d. Enforce drawing requirements for alloy verification.

6. Surface Cleanliness. Components frequently have stringent cleanliness requirements to assure proper operation in critical applications to avoid adverse reaction with the environment or to assure successful coating, bonding, or other manufacturing process. Despite these needs, practical quantitative, industrially applicable techniques do not seem to be available.
   a. Make investigation into the potential of reflection or scattering for the detection of contamination or embedded particles from processing such as grit blasting.
   b. Study low energy alpha or beta particle attenuation or scatter as a potential tool for cleanliness measurement.
   c. Examine high frequency ultrasonic waves for possible impedance changes on contaminated areas.
7. Residual Stress. The magnitude and sign of a residual stress in a part caused by manufacturing or service can be an area of uncertainty in stress analysis. Current methods have limited applicability. Advanced development is needed to improve existing techniques and to adapt potentially applicable NDE techniques to residual stress problems.
   a. Investigate advanced ultrasonic techniques for the detection of stress.
   b. Make ultrasonic and x-ray diffraction equipment for the measurement of stress more quantitative and more portable for field applications.
   c. Investigate the possibility of using specialized eddy-current techniques to detect residual stress.
8. Fatigue. Insufficient knowledge is available on either the precursors leading to fatigue or appropriate NDE techniques to detect the precursors. Improved methods are needed to follow fatigue progression and to predict fatigue life.
   a. Develop NDE techniques for identifying precursors of fatigue cracking.

b. Produce equipment for use in situ on complex systems to detect precursors and to monitor progress on fatigue damage.

9. Thin Materials. Instrument limitations have retarded application of NDE techniques to the evaluation of thin materials. Examples of needed development are: higher frequenc eddy current and ultrasonic instruments, and smaller test probes to achieve greater sensitivity and resolution to small flaws.

   a. Make existing techniques more sensitive and quantitative.

   b. Develop improved Lamb-wave ultrasonic and high-frequency eddy-current equipment for rapid inspection of large surfaces.

10. Corrosion and Stress Corrosion. Nondestructive evaluation techniques are needed for the detection and evaluation of corrosion in hidden areas.

    a. Develop improved correlation between NDE results and the state of corrosion.

    b. Make radiographic, ultrasonic, and eddy-current instrumentation more versatile and portable for field application.

    c. Investigate radiation and ultrasonic scattering techniques, coupled with data correlation methods.

APPENDIX A

NDE Programs Listed in Materials Advisory Report MAB-231, "Long Range Aerospace Manufacturing Developments"

In the two volumes of MAB-231, Long Range Aerospace Manufacturing Development, there are five programs that are exclusively NDE. Twenty-five of the manufacturing programs contain substantial NDE program references:

M-101	M-501	M-701
103	502	702
115	512	703
127	516	704
	523	705
M-201	526	
219	533	
M-403	M-603	
407	611	
410	623	
430	625	
	688	
	629	
	630	
	631	

SECTION V

Special Phenomena

MEMBERSHIP OF THE PANEL

H. Berger, Chairman

J. H. Cahn

G. J. Posakony

FOREWORD

Nondestructive evaluation (NDE) presently uses many different disciplines to study and evaluate the integrity of materials. As in other scientific areas, great strides are being made. However, cross-fertilization of disciplines, increased knowledge, and improved instrumentation capability offer further advancement in possibilities. This Special Phenomena section deals with the recommendation of development areas where still greater studies for proving the quality and serviceability of materials can be made.

CONTENTS

ABSTRACT

Several new scientific techniques offer potential solutions to the problems of nondestructive evaluation of material integrity. The text discusses techniques, novel approaches and their potential application to NDE. Priorities for development work are assigned to areas of nondestructive investigation which promise improvements in testing capabilities. The study of failure mechanism is recognized as important and necessary to assure that material imperfections which lead to failure can be measured by nondestructive means.

Investigations in data processing methods would lead to improved interpretation in all nondestructive tests, and it would make feasible concepts such as the energy signature approach. The laser is cited as a new nondestructive tool for areas such as metrology, surface cleanliness studies, vibration detection generation and analysis, and holography. The potential of the holographic imaging techniques is discussed for light, ultrasound, neutrons and other regions of the electromagnetic spectrum. Acoustic emission is recognized as a potentially powerful tool for nondestructive evaluation. This passive listening method offers promise as an in-service inspection for revealing conditions of impending failure. Characterization of material properties may be revealed by study of acoustic propagation of a particular ultrasonic vibration mode or new uses of ultrasonic modes as applied in NDE. Ultrasonic microscopy could provide very different material information from that obtainable by other microscopy methods. Unexplored areas in the electromagnetic areas of microwaves, electric fields, ultra-violet, and soft x rays appeared especially promising for NDE. Particle radiation techniques which could be more fully utilized were alpha particle and electron studies for analysis of surfaces, cosmic rays for in-place inspection of heavy structures, and the use of neutrons, both for radiography and activation analysis.

The Committee recommends that development efforts be pursued in the priority listed and that the science area be continually scrutinized for novel techniques and ideas potentially useful for nondestructive examination. The sponsoring of periodic brainstorming sessions with scientific specialists in appropriate disciplines is suggested as a scrutinizing method.

I. INTRODUCTION

While much of this over-all committee report is concerned with presently available nondestructive evaluation techniques and with methods by which they can be applied in certain problem areas, the report would be incomplete without an evaluation of phenomena which might prove useful for future NDE requirements. Phenomena new to NDE technology and major variations of presently-used test methods are considered here in the light of their potential to future test needs.

These techniques are discussed in sufficient detail so that the reader can grasp the method and gain some appreciation for its spheres of usefulness and needs for further development. A bibliography provides more detailed information for those who desire it. An assessment of the priority for development of these phenomena is presented.

Before turning our attention to specific methods, we would like to discuss briefly a topic that we believe as important as the specific areas to be detailed in the section entitled Special Phenomena.

First, we define the concept of serviceability. In general, serviceability of a component is its fitness for operation in a given engineering application. In particular, serviceability is a combination of chemical, physical, and structural properties that assure satisfactory performance for a predetermined time in a particular engineering environment created by chemical and physical factors. The ultimate goal of nondestructive evaluation is the determination of serviceability.

The analysis of failure mechanisms is the cornerstone upon which rational decisions of serviceability are made. This analysis should determine the properties, characteristics, and attributes of importance and define the performance limits of materials and components. Since serviceability is dependent on design, materials, processing, and operating environment, there will be several modes of failure and many characteristic levels of performance. Various nondestructive methods might be required with techniques tailored to the specific object. Generally, nondestructive evaluation techniques do not directly measure a property but rather measure a property that is correlated with the characteristic of interest.

In Appendix A, the application of novel nondestructive test approaches to particular problem areas is discussed.

The Panel on Special Phenomena is responsible for the choice of areas of projected research in the report. The judgment, however, was based on personal knowledge, selected from library data and aided by contact with many other individuals within the Committee and throughout Government and industry. To acquaint the Panel with the latest developments of science that might have application to nondestructive evaluation, experts from many different fields were invited to give presentations to the entire Committee. On January 25 and 26, 1968, a special "brainstorming" session was held at the National Academy of Sciences Building in Washington, D. C. Participants at this meeting included experts in electromagnetic theory, holography, microwave, infrared, acoustics, penetrating radiation, signal processing and compression. Participants listed on pages I-v and I-vi included individuals from industry, education, research, Air Force, Army, Navy, NASA and DOD. The object of these sessions was to apprise the Committee and the Panel of the latest developmental work that was being performed and to provide new areas which showed potential for NDE. In addition to the meetings, questionnaires requesting "second thoughts" were sent to all persons who participated in the discussions. The output from these special meetings was most helpful to the Committee and the Panel in assessing the state of the art and in making recommendations.

II. SPECIAL PHENOMENA

Fruitful areas for research and development to advance the science of nondestructive examination of materials are discussed here in the order of priority assigned by the Committee. The priorities are based upon three factors:

i Orderly growth of the subject,

ii Universality of the development,

iii Immediacy of the payoff.

Priority 1: Data Processing/Correlation Techniques

The application of sophisticated data processing methods to present NDE can be of great value. The following considerations indicate that the equipment and methods are to supplement the existing techniques of data display with the developing new methods of signal processing:

A. Integrated, discrete, and hybrid active circuit modules have increased in variety and availability with considerable reduction in cost. Units such as operational amplifiers, function generators, functional transducers, multiplier-dividers, and innumerable types of logic modules can now be employed in quantity on problems where the cost of these components would have been prohibitive a short time ago.

B. It is now practical to consider systems employing small digital computers especially adapted to process control and on-line data processing. Such units are readily equipped for interfacing with analog systems and large general-purpose computers.

C. New data-reduction processing methods are developing rapidly under the impetus of military and space needs. It should be possible to modify many of these techniques to the needs of nondestructive evaluation.

The availability of these new devices and techniques permits considering the use of active filters and nonlinear operations of quite complex forms, implemented by equipment which is relatively inexpensive and easily fabricated. Such equipment can provide real-time indications backed up by more complex time-lapse methods exploiting the ready availability of the large general purpose computing facility.

The use of correlation techniques needs to be further explored, both in real-time and in storage-time lapse. The use of real-time correlation may involve the comparison of immediately adjacent areas and concentrate on the amplified difference signal produced by variations in bulk properties of the material. For example, by oscillating the motion of thin specimens, it is possible to determine differences in temperature of 1/10 of a degree centigrade between two points separated in a space by 10 microns. A second example involves the detection of cracks of micron depth

in a microwave reflection scheme; the crack radiation differs in mode from the normal reflection and hence is separable by correlation methods. The use of real-time correlation also can be achieved by comparing signals with those from prepared samples.

Comparison can also be based on the cross-correlation between signals from the object under investigation and signals previously stored by electronic means. Such techniques can be generalized to include one or more signals which together form the energy signature of the object under investigation, and by a process of electronic or optical storage, a time-lapse signal correlation can be achieved. (See Appendix A.) Time-lapse studies can be carried out using magnetic tapes, film storage, and holography. Demonstrations of correlation techniques have shown up to three orders of magnitude of increased sensitivity over conventional techniques.

Closely related to correlation techniques is the use of matched filters, sometimes called correlation detectors, for detecting anomalies whose forms are known. These methods are developing rapidly in the fields of radar and sonar, and new developments should be watched for applicability to nondestructive evaluation. At present, the techniques are applied mostly to frequency-modulated signals, whereas many of the signals of interest are not transmitted on carrier channels. However, it might prove practical to introduce a carrier to take advantage of the characteristics of matched filters currently available. In pulsed carrier testing, such as ultrasonics, a more direct application may be possible.

The rapidly developing area of pattern-recognizing systems should be closely watched for applications, since it is devoted to problems having much in common with those of nondestructive evaluation. Early work in such systems was primarily directed to machine recognition of standard patterns such as those cataloged for electrocardiograms and the account numbers on checks. The idea of a "pattern" has been generalized to mean the components, at a given observation time, of any vector-valued signal. Such a pattern could be the set of <u>n</u> readings from an <u>n</u>-channel test system at a given sampling instant.

The above systems require the use of techniques which in themselves may be useful, for example, decision filters, Bayesian estimates, cost function criteria, linear programming, and discriminant functions. Certain linear real-time filters, such as those yielding coefficients in the expansion of a signal into a series of orthogonal functions, may also find application.

Various forms of signature analysis, correlation and filtering, can be performed by digital computers. The limitation of digital computer techniques is system bandwidth. A new method of optical storage of information provides an expanded bandwidth system that gives rapid access for large volumes of data. This development may be important in present and future requirements for monitoring serviceability of materials.

Priority 2: Laser Techniques

The word "laser" is an acronym for Light Amplification by Stimulated Emission of Radiation. The laser is a device which emits coherent light. that is, light in which a definite phase relationship exists between two given places in the light wave train (spatial coherence), and which has essentially a single wavelength (temporal coherence). These devices provide an intense, well-collimated beam of coherent light which can be continuous or pulsed. Here, we consider the application of these devices; holography is considered separately in this report.

In the field of nondestructive evaluation, the laser provides a useful tool by virtue of several of its characteristics. Since it is a well defined, intense source of light, it can be very useful for many visual inspection problems, particularly those in which advantage can be taken of the small angular divergence of the laser beam. Also, materials can be examined for reflectance, absorbence, or transmittance characteristics by observing changes in intensity as the materials are placed or moved in the laser beam or in the laser cavity. Polarized, coherent light is very sensitive to phase changes in propagating through matter, and thus variations in density, strains, bubbles, and other defects are readily observable with the laser.

For interferometry the laser provides a useful tool to determine thin film thicknesses, surface deformation and similar characteristics. As a profilometer, the laser can provide the capability for measuring distances in the microinch range with accuracies better than 1 part in 10^7.

A particularly inviting laser capability which has not been exploited fully for nondestructive evaluation is the generation and detection of ultrasonic energy. Since these techniques do not require physical contact with the object under test, this offers a tremendous advantage.

Lasers have been used as heat sources for such applications as drilling or welding. They also offer potential as heat sources for vaporizing materials for analysis.

These application areas, for the most part, involve lasers in the strict meaning of the word, that is, devices which emit visible radiation. For nondestructive evaluation and for this report, it is desirable to broaden this definition to include similar devices which emit electromagnetic radiation. Microwave, infrared, ultraviolet, and other portions of the electromagnetic spectrum are all potentially useful for nondestructive examination.

Priority 3: Holography

Holography is imagery by wavefront reconstruction. For light holography, the object to be photographed is illuminated by coherent light (typically from a laser). Light reflected from the object, or transmitted through a transparent object, is allowed to reach a photographic plate, as is coherent light which has not been directed at the object. At each point on its surface, the photographic plate records light from every illuminated point of the object and the interference of this light with the reference light beam from the source. Therefore, the hologram is a record of both amplitude and phase, as a result of the interference of the coherent beams from the object and the source.

If one observes a hologram, the photographic record of holography, with a coherent light beam (as from a laser), the light interacts with the recorded fringe patterns to regenerate a new wave field that is identical to the one originally recorded. The observer will see the wave field as if it were emanating from the real object. He will see the object with the usual visual appearances such as three dimensionality and parallax between near and far portions.

Holography need not be limited to light; here lies the key to the great potential of this technique for nondestructive evaluation. Holography can, in principle, be performed with any wave radiation such as the entire electromagnetic spectrum, and other forms of energy including ultrasound and neutrons. The holographic use of penetrating radiation such as ultrasound, x rays and neutrons holds forth the promise of three-dimensional views of opaque objects outlining the position and severity of discontinuities. Among the many potential areas of usefulness are the following:

A. Light

Most holographic work has been done with light. For stress and vibration analyses by nondestructive evaluation, light holography promises to be useful as a strain gage and as a detector of material surface deformations which precede failure.

B. Ultraviolet and Infrared

Coherent radiations of these types offer promise for holographic studies of material surfaces to determine uniformity of coatings, surface cleanliness, and to detect surface cracks which have developed in service. These two radiations would provide sensitivities to different materials and surface layers than light because of their different reflection and transmission characteristics.

C. Microwave

Microwave holographic correlation techniques have been shown to be useful for detecting surface cracks on metal objects. Microwave holographic techniques could also provide three-dimensional images of dielectric materials.

D. Ultrasonic

Coherence characteristics of ultrasound make it attractive for holographic applications. It appears to be capable of providing three-dimensional ultrasonic images in which one could detect unbond, cracks, and other inhomogeneities which produce ultrasonic impedance variations.

E. X Ray

Holography with x-radiation has been partially accomplished. It offers promise for making three-dimensional images of internal details of objects with tremendous magnification possibilities (because of the great difference in wavelengths between the x-ray imaging radiation (~ 1 Å) and the visible viewing radiation (~ 5000 Å).

These techniques, particularly in the case of x-ray and ultrasound holography, appear to be useful for problems which require precise information about the location and extent of flaw areas within opaque inspection objects. The capability for viewing such holograms three dimensionally offers this advantage. In the case of x-ray holography, the large magnification potentials present the possibility for examining materials on a micro scale.

Consider the ultrasonic holographic examination of a bonded assembly. The holographic view might yield information on both the area and orientation of any bond inhomogeneity, and its depth within the structure or bond layer. The magnification possibilities with x rays might enable resolving a distance about equal to the x-ray wavelength (say, an Angstrom). This would permit one to observe atoms, to study dislocations, and to detect very low levels of foreign atom concentration. On a scale involving less magnification, x-ray holography would eliminate much of the need for tomography or stereo radiography because of the three-dimensional properties of the image.

A practical limitation is that relatively long times may be involved in the production, processing and subsequent viewing of a hologram. Such time lags are

always problems for nondestructive evaluation. On the other hand, proposals for a real-time ultrasonic holographic system have been reported, so that some work on this limitation is already under way.

Another practical problem, which leads into the discussion of future development needs, is that no one has published holograms which display subtle changes. Ultrasound holograms have involved, for the most part, objects with holes in them, or other high contrast objects. One wonders if these initial demonstrations may be misleading* in that it may be difficult to display some of the subtle changes which should be detected in a good nondestructive testing system.

The limitations discussed above indicate needs for further development. Certainly the real-time ultrasound holography system development should be pursued. Further work on more representative nondestructive test samples as ultrasound holography objects should be done.

In the x-ray area, the real need is the development of a coherent x-ray source of reasonable intensity. Although an x-ray laser does not now appear to be technically feasible, one can hope for the development of a reasonably coherent source of x radiation. Once this is accomplished, work can proceed on the development of x-ray holographic detection and viewing techniques.

Priority 4: Acoustic Emission

Materials under stress emit noises or sounds. These phonon emissions are generated by movements resulting from such things as crack propagation, slip steps, the unpinning of blocks of dislocations, phase changes and more subtle micro movements. Acoustic emission signals have been measured at frequencies from the low audio range to several megahertz. However, only signals above the audible range are used due to the influence of ambient background noises which are not related to material properties. Generally, the range used for emission studies is 30 to 300 kHz.

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* As were the early demonstrations of stereo-fluoroscopy, for example. At the light levels normally available with fluoroscopy, only high contrast objects could be viewed in stereo.

Studies can be logically divided into two categories:

A. Macro Phonon (Acoustic) Emission

B. Micro Phonon (Acoustic) Emission

The classification of macro and micro phonon emission is based on the signal levels resulting from the applied stresses. Crack propagation, liquid boiling, breakdown of components in a composite structure, and martensitic type phase changes are examples of macro emissions. Instrumentation for these studies should be capable of amplifying and recording information in the millivolt region.

Energies from more subtle changes such as metallurgical slips, dislocations and diffusion controlled phase changes are examples of micro phonon emissions. Instrumentation for these studies should be capable of amplifying and recording information in the microvolt region.

A. Macro Phonon Emission

Acoustic emission is being used successfully to identify and monitor crack propagation generated through welding. The stress introduced during the welding process is sufficient to start the initial cracking and no further stress need be applied as long as the propagation continues. Stress applied through hydrostatic, pneumatic, machine or service testing can supply additional forces which can cause additional cracking. This real time crack progression can be analyzed from its initiation to its end condition.

Other areas presently being investigated include studies of boiling points of liquids and dynamic distortion analysis of composite structures such as missile cases and nonmetallic honeycomb structures.

B. Micro Phonon Emission

Real-time understanding of the dynamic processes which precede failure is a vital portion of materials research. Emission detected during studies of plastic deformation, degree of deformation, characterization of material properties, and phase changes (diffusion controlled) offer promise for enumerating factors which

contribute to material deterioration. Other areas being studied include stress corrosion cracking and adhesive bond strength.

Micro phonon emission studies offer far-reaching potential. Most of the studies are in an infancy stage. Major emphasis remains on development of instrumentation, techniques, and applications.

Expanded studies into the micro phonon emission regions are considered essential for better understanding of the mechanisms of failure. The phonon energies studied to date should not be construed as a limit. Studies of the basic phonon spectrum of the crystal structure offer keys to the further understanding of materials.

Priority 5: Acoustic Wave Propagation Studies

The propagation of the acoustic energy used for materials testing is influenced by the conformation and properties of the material under evaluation. Ultrasonic energy is initiated at the transducer in a pattern and mode peculiar to the transducer design; however, as it propagates through the material or through various interfaces, the acoustic energy may be altered in mode, direction and pattern. The acoustic propagation pattern is influenced by such factors as: sound beam characteristics, boundary conditions of the material, attenuation, mode conversion, shape and contour of the specimen under test, testing frequency, impedance of the various interfaces, sound velocity of the various media, shape and contour of the material defect, etc.

The predominance of testing today uses the simpler forms of energy, such as the longitudinal, shear and surface wave modes. There is significant information available in the acoustic wave that is not now being used. Development of ways to expand the use of available acoustic information seems to hold excellent promise and advantage in ultrasonic nondestructive evaluation. Some of the potential areas that hold promise for providing more definitive data on material defects and material properties include:

A. Characterization of material properties through analysis of the amplitude and the frequency spectrum of the transmitted and reflected waves.

B. Study of the phase relationships between acoustic waves to define interface and defect character.

C. Analysis of the acoustic energy modes reradiated from a defect to identify type.

D. Generation, separation, and use of discrete waves of acoustic energy for materials evaluation (Borkowski, Lamb, Love, Stoneley).

E. Generation and use of a broad spectrum of ultrasonic frequencies. This coupled with spectrum analysis could provide both a material and/or defect signature.

F. Use of ultrasonic Schlieren techniques (visual) to locate defect areas in materials.

G. Study of frequency shifts and spectrum filtering to evaluate material properties.

The amount of progress that can be made by continuing to use the simpler forms of energy is limited. Ultrasonic nondestructive evaluation must expand into use of more sophisticated acoustic spectrum, phase and frequency analysis if significant improvements are to be made in the testing method. There is apparently no technical reason why the more complex modes could not and should not be employed.

<u>Priority 6: Ultrasonic Microscopy</u>

There are several groups working on ultrasonic imaging techniques. The highest frequencies that are being investigated are in the order of 10 MHz. Ultrasonic imagery is relatively far advanced and instruments are commercially available. Ultrasonic microscopy, on the other hand, has not been pursued to the point that the technique has been demonstrated.

In the 1930's Sokoloff proposed the ultrasonic microscope. In the text of allied articles, descriptions were made for excellent detailing of macroscopic structure within metallic parts. Researchers have been unable to substantiate Sokoloff's work, but there appears to be no technical reason why an ultrasonic microscope could not be developed if the proper sources, detectors, and lens structures were available.

It would be necessary to work in the very high ultrasonic ranges, perhaps as high as several thousand megahertz. With the recent advent of thin film piezoelectric semiconductors these frequencies are attainable. The problems are great but the rewards would be tremendous. Efficient funding for such a project might provide a new and valuable tool for nondestructive testing.

Priority 7: Electromagnetic Spectrum Studies

Although electromagnetic radiation provides some of the more widely used tools for nondestructive evaluation, portions of the electromagnetic spectrum could be more fully utilized. Even in spectrum areas which are well utilized, modifications in technique offer a potential for much improved information yield.

For example, in the use of x radiation for nondestructive evaluation, much more significant test information apparently could be obtained if transmitted, scattered or fluorescent x rays were analyzed for both energy and intensity. Semiconductor detectors make it feasible to do so with an energy resolution of a few Kev. If we are to obtain the most information from such a test, the x-ray source will require additional development to provide either an intense monochromatic beam or a relatively constant yield over a wide range of wavelengths. We should also consider the possibility of further decrease in focal spot to bring microradiography into greater use, and we should consider novel methods of generating x-ray voltages so that field use of x-ray equipment might be made easier. In this latter regard, the piezoelectric approach looks promising. It should also be recognized that the soft x-ray region has been relatively little used. It offers a good potential for the examination of surfaces and coatings. X-ray methods for stress analysis could hopefully

be improved so that the technique could be more widely applied. Finally, in the x-ray area, the use of correlation methods merits attention as a means for improving the sensitivity of this important test method.

Eddy-current methods of inspection are widely used but improvements here also offer promise. Hall detectors for eddy-current fields have come into use recently; more detector research may be justified. Of perhaps greater importance are studies to better understand and to improve the methods of generating the magnetic fields which probe the inspection object. Greater control of field orientation would yield more reliable defect detection.

Microwave methods are slowly coming into the arsenal of the nondestructive evaluation engineer. The potential is much greater than has thus far been demonstrated. The technique promises to be useful for investigating the integrity of nonmetallic materials, for measuring dielectric properties, for determining moisture content, degree of cure of resins, and for examining surfaces. Microwave techniques must assume a greater role as nonconducting materials come into wider use. Similar comments apply to the use of infrared test methods which should also be somewhat easier to apply to materials which have relatively poor thermal conductivity. The demonstrated application of infrared test methods to examine electronic components shows what can be done if the method is properly applied.

In addition to these areas for which improvements are suggested, there are portions of the electromagnetic spectrum which are very little utilized, for example, the ultraviolet range. Ultraviolet radiation could be used to examine surfaces for contaminants and coatings and to study transparent materials.

In summary, electromagnetic radiation could provide much greater potential for nondestructive examination if unused portions of the spectrum were exploited and if more sophisticated use of those areas already employed for testing were made.

Priority 8: Particle Radiations

Many particle radiations are not used at all, or only very little, in testing and analysis applications. There are excellent possibilities for making use (or greater use) of radiations such as electrons, alpha particles, neutrons, cosmic rays, protons, and muons in radiography, gaging, backscatter techniques, and activation analysis.

Alpha particles and electrons show promise for surface studies to detect and quantitatively determine contaminants, coatings, and surface composition. These radiations can be used both in backscatter studies of surfaces and for through-transmission gaging or radiographic studies of thin, light materials. Alpha particles also show promise for activation analysis. Alpha and electron techniques can be used in an x-ray fluorescent type of analysis. Both radiations are attractive for field problems because of the portability of radioactive sources.

Cosmic rays and muons could be utilized for through-transmission inspections of large, heavy in-place structures such as building supports, dams, etc.

Neutrons are being applied to nondestructive evaluating problems in activation analysis, in scatter studies (mainly to determine hydrogen content of soils, slurries, etc.) and in radiography. Much more could be done, particularly in the latter area, if greater use of neutrons outside the thermal energy region were made.

More information could be gained from examination using particle radiation systems if measurements of both energy and intensity were analyzed and if comparisons were made with similar data for known inspection materials. This correlation approach could add substantially to the sensitivity of these techniques. Recent developments in solid state detectors for penetrating radiation add to the practicality of combined energy and intensity measurements.

The basic tools are developed for performing most of the suggested inspection techniques. The major need appears to be communication between the technique developer and those with the problems. Symposia, such as the recent

ones on Radioisotopes Applications for Aerospace (see Bibliography) are a step in that direction.

Neutron techniques require additional development in the areas of nonreactor neutron sources (in all energy ranges), in image systems with improved resolution and motion capability for the thermal neutron energy range, and in image detection systems for the higher neutron energy ranges.

Priority 9: Other Novel Techniques

Several other novel approaches for nondestructive evaluating methods have been discussed on a Committee level. These techniques offer somewhat less promise for immediate development than the techniques listed previously in this report.

The Mössbauer Effect may offer a novel test technique for surface investigations, particularly to study adhesives and surface and substrate attributes. The technique depends on the fact that changes in energy level spacing due to changes in the s-electron density at the nucleus shift the resonance energy. Such changes may be observable due to chemically absorbed materials such as oxides at the surface. This is known generally as the isomer shift. Another effect, quadrupole splitting, measures the effect of an electric field gradient at the nucleus. This field gradient may be produced by foreign surface atoms. However, the fraction of atoms involved is very small, since only the surface atoms contribute.

Nuclear Magnetic Resonance (NMR), like Mössbauer, can detect electric field gradients due to strains and impurities in the substrate. It, too, will be limited by the surface atoms being a small fraction of the total observed, since the skin depth is still large compared to the surface layer. If one puts specific materials such as hydrogen into an adhesive, the environment of this material may be drastically altered due to chemical bonding to the substrate, affecting the proton resonance. Again, the fraction of material making the bond will be small.

Paramagnetic Resonance, like NMR and Mössbauer, is limited to specific materials, in this case unpaired paramagnetic ions. Impurities, such as metal ions intentionally added to adhesives, might prove successful in indicating bond, due to changes in the electrostatic environment.

III. CONCLUSIONS

The novel techniques discussed in the previous section of this report all offer excellent potential for the advancement of nondestructive evaluation and for the resultant improved reliability of materials and components. The suggested order in which near future development of these ideas should be pursued is as follows:

1. The Panel recognizes the necessity for a study of failure mechanisms as applied to the bulk material and to bonding. Measurable material properties that are truly important to a realistic prediction of failure must be determined. Knowledge of these properties is a requisite for the preparation of meaningful specifications and is vitally important as applied to in-service inspection.

2. Of almost equal priority is a thorough study of methods of data collection and signal analysis techniques to improve and expedite data processing, because of their wide application and potential for immediate payoff. The study should include the development of generation and detection techniques which lend themselves to data storage and correlation methods. The correlation technique vastly increases the sensitivity of all known nondestructive techniques. Signals from test specimens could be correlated with those from a known good component or from an ideal. The data processing study will also lead to the capability for handling and interpreting more than one type of information from a given test. X-ray studies could be expanded to include energy differentiation as well as intensity variation. Ultrasonic testing could be improved by simultaneous measurement of phase, frequency, and intensity. The capability for data storage makes possible the implementation of the energy signature concept in which one records and continuously compares thermal, vibratory, magnetic, etc. profiles of an assembly in service (see Appendix A). Such data

should indicate a change in the unit under examination, and would hopefully lead to a realistic determination of the time for replacement of the unit.

3. The laser provides the best new tool to appear on the NDE horizon. The spectral purity of the laser makes it a particularly useful tool for interferometry. Dimensional measurements in the order of microinches are feasible. Applications include metrology, surface cleanliness studies, and surface deformation due to stresses or waves (for example, for the detection of acoustic waves). As an intense radiation source, the laser has applications in areas such as the visible (stress), infrared (thermal), and ultraviolet (fluorescence). It also has application as a source to locally vaporize materials for spectroscopic analysis. The laser is also capable of generating ultrasonic surface waves and offers the advantage of a non-contact approach.

4. Holography with the laser is a recent advent and, while its complete development may be of a long-range nature, its potential is enormous. Holography has been successfully demonstrated with light, microwaves and ultrasound. Ultraviolet and infrared holography appear to be feasible and applicable to surface studies. X-ray holography has yet to be developed but offers tremendous potential from the standpoint of image magnification and three dimensionality. X-ray holography is predicated on the existence of a coherent source other than an x-ray laser. Ultrasound holography also promises significant payoff; it requires further development.

5. Next in the order of priority is the field of acoustics. Acoustic emission can be an important indicator of the condition of the inspection object, both during fabrication and in service. The main field of acoustics naturally divides itself into two major research areas, both of which appear to be profitable from the non-destructive evaluation point of view. One is the generation and launching of particular wave modes such as the various types of surface waves. The other is the influence of the transmitting material properties on the propagation and resonance characteristics. There is presently a large body of knowledge relating imperfections and defects in single crystals to acoustic measurements. What is needed is the

expansion of this knowledge to engineering materials. Yet another area is the expansion of ultrasonic imaging techniques to the very high frequency range; this might lead to the very important development of ultrasonic microscopy.

6. There are unexploited areas of the electromagnetic spectrum. Microwave techniques to determine dielectric properties and to study surface phenomena require further development to reach their full potential. Research in eddy-current methods is recommended for the development of new detectors and the novel orientation of probing fields. Ultraviolet and soft x-ray techniques appear promising for surface investigations for both contamination and film thickness measurements.

7. Finally, it is recommended that further studies be conducted in the use of particle radiations for nondestructive examination. Alpha particles and electrons show promise for surface studies. Both are attractive for field applications because of the ready transportability and availability of isotopic sources. Cosmic rays and muons appear useful for in-place inspection of heavy materials. The usefulness of neutrons for activation analysis and radiography has been demonstrated but significant advantages appear possible if greater use of neutron energies outside the thermal region is made.

IV. RECOMMENDATIONS

To recapitulate, the order of presentation of topics has been determined on the following basis:

i Orderly growth of the subject,

ii Universality of the development, and

iii Immediacy of the payoff.

On the basis of these criteria, it is recommended that research and development efforts be pursued in the following areas, with the priorities indicated by the order of the listing:

1. Data Processing. Improved data processing techniques will permit many testing methods to yield more information than is presently attainable.

2. Laser Techniques. The advent of this potentially useful device must be applied, where possible, to nondestructive analysis. It shows promise in metrology and highly selective electromagnetic spectrum applications over a wide wavelength region.

3. Holography. The use of phase sensitive detection promises useful detection of inhomogeneities correlated with serviceability.

4. Acoustic Emission. The spontaneous generation of acoustic signals recording the temporal behavior of a component has great promise for nondestructive evaluation.

5. Acoustic Propagation. Further research is needed to make available the rich spectrum of acoustic propagation modes for nondestructive testing.

6. Ultrasonic Microscopy. Due to the relative ease of ultrasonic transmission in many engineering materials, a great enhancement of available information would be effected by the development of ultrasonic microscopy.

7. Electromagnetic Spectrum Studies. Extension of the presently-used parts of the electromagnetic spectrum is clearly indicated, particularly as regards surfaces and semi-transparent materials. Research is still essential in those areas of the spectrum presently used, particularly microwaves.

8. Particle Radiations. The use of electrons and neutrons are now fairly well established in nondestructive evaluation practice, although further research is indicated. More esoteric particles such as the muon must be considered as a potential contributor to nondestructive evaluation.

This completes the list of priority items drafted by the Panel. In addition, we have included a short list of novel techniques which, for stated reasons are slower in developing. In this connection, the Panel recommends that further brainstorming sessions on an annual basis be instituted to review developments and to suggest new techniques of great potential. These annual meetings to be effective must be carefully planned; in particular, the participants should be fully alerted to the potential application of their special areas of competence to nondestructive evaluation.

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APPENDIX A

SPECIFIC PROBLEM AREAS AND POTENTIAL SOLUTIONS

Although some reference has been made in this report to the application of novel nondestructive evaluating techniques, it may be appropriate to indicate potentially useful nondestructive examination techniques for specific problem areas, as discussed elsewhere in this report. One major problem area is that of in-service inspection. If use is made of information collection and storage techniques as discussed in the text above under the heading, "Priority 1: Data Processing/Correlation Techniques," one approach to the problem is the energy signature concept. A complete description of this approach is as follows:

Every part that emits energy as a function of its operation has a signature that is characteristic of normal operation. The energy signatures are the acoustic, electromagnetic, thermal, and magnetic et al., patterns that are associated with the operating conditions of the mechanical and electrical parts, components, or assemblies.

An electrical pump and an electrical relay provide examples which describe the concept.

A. Electrical Pump

The signatures that could be anticipated include:

(1) Infrasonic (low frequency vibrations in both the motor and pump).

(2) Sonic (noise in both the motor and the pump).

(3) Ultrasonic (noise associated with motion related to normal conditions, probably would fall in the 25-35 kHz range, -- not acoustic emission).

(4) Ultrasonic (acoustic emission).

(5) Electromagnetic (arcing in the motor or brushes).

(6) Magnetic (magnetic field pattern).

(7) Thermal (temperature rise in motor and particularly in specific areas of the motor).

A combination of the individual signatures provides an energy signature of the system.

B. Electrical Relay

(1) Infrasonic (low frequency vibrations).

(2) Sonic (noise pattern of operation to determine normal and abnormal closure).

(3) Magnetic (flux field pattern and field strength).

(4) Electromagnetic (R. F. noise generated when the contacts make and break).

Every component or system that has energy signature can be correlated with the signatures from like structures. If there is an abnormal signature, it can represent a defective part or it may determine remaining life of the part. The unique phase of the concept is that energy signatures can include several different energy forms and a combination of signatures may provide the key to analyzing performance.

Characteristic signatures can be recorded on film or tape and potentially can be used in comparator circuitry or computer programming.

The use of energy signatures is not new. Engine analyzers, leak detectors, and thermal paints are examples of devices used for obtaining signatures.

We are only in the initial phases of development of the over-all concept. Once developed, it would be useful in innumerable areas. Rotating machinery, engines, friction brakes, hydraulic and electrical pumps, integrity of structures, such as bridges and buildings, bearings, and any other item to which energy is applied.

Advantages to the concept include:

A. Simplicity of implementation.

B. Use of the part to evaluate itself.

C. Possibility of predicting remaining life.

D. General applicability to many parts, both electrical and nonelectrical that are not now routinely inspected for integrity.

Limitations include:

A. Not readily applicable to static systems.

B. The catalog of signatures for any one item may be relatively great.

To reach full utilization of the concept, developments must include:

A. Generating and cataloging the characteristic signature from specific parts, components and systems.

B. Analysis of the importance of the change of signatures as related to life expectancy.

C. Methods for display of information relating signatures of original manufactured goods with present signature characteristics.

D. Selection of instrumentation that could be used for signatures, such as magnetic leakage, acoustic, and electromagnetic.

While the idea of signatures is not new, the reduction to general usage has not been attempted and remains to be accomplished.

Additional problem areas and some suggested potential solutions are given in outline form:

1. <u>Metallic Alloy Identification</u>

A. X-ray fluorescence with a comparator, correlation technique.

B. Improved (and perhaps instrumented) chemical spot tests.

C. Chemical tests including analysis of liberated gases.

D. Devise tests for attributes which make the particular alloy useful--for example, measure hardness or other desirable property of alloy.

2. Coatings

A. NMR methods to determine quantitative bond strength (adhesion by means of chemical bond).

B. Mössbauer techniques to determine quantitative bond strength (as in A).

C. Acoustic emission methods.

D. Ultrasonic microscopy.

E. Holographic comparator techniques.

F. Electrostatic methods to test nonconductive coatings.

G. Chemical tests.

3. Surface Cleanliness

A. Holography (visible or microwave to examine for surface particles; these and ultraviolet and infrared to examine surface for contaminants).

B. NMR and Mössbauer techniques to detect contaminant materials.

C. Ultraviolet fluorescence or reflectivity.

D. Activation analysis (particularly by alpha particles to limit radiation analysis to surface layers).

E. Electric stylus scanning (determine surface contact potential).

F. Chemical tests.

4. Materials Joining

A. Adhesive bonding.

To quantitatively determine bond strength, one could consider:

(a) Acoustic emission tests

(External stress to generate emission could be generated by thermal, sonic, microwave, mechanical, etc. methods.)

(b) Acoustic spectrum studies

(These might yield information such as degree of cure, brittleness, etc.)

B. Metallurgical bonding.

(a) Ultrasonic microscopy (perhaps combined with holography for complex shapes).

C. Welding

(a) Thermal property measurements during welding to regulate heat and to determine thermal properties of weld.

(b) Acoustic emission

(c) Ultrasonic holography

D. Brazing

(a) Neutron radiography to determine presence or absence of neutron sensitive (Ag, Cd, B) brazing materials.

(b) Acoustic emission.

5. Composite Structures (Fiber and filament reinforced materials)

A. Electromagnetic field tests.

B. Ultrasonic schlieren techniques.

C. X-ray holography.

D. Propagation of ultrasound.

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APPENDIX B

RADIATION

by

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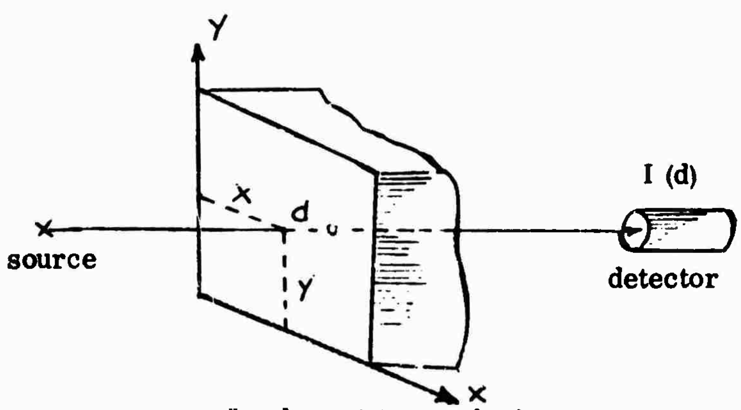
In the following notes, I collect some of the information that could conceivably be of some use for nondestructive testing. However, since I am a complete non-expert, many of the remarks may be trivial or useless or both.

1. INCOHERENT AND COHERENT PROCESSES

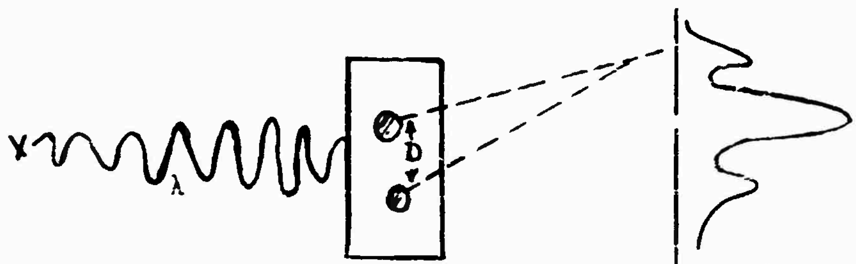
The following two processes are the two extreme cases that can appear in the study of solids and liquids by radiation. In the incoherent case, a beam of particles passes through an object and the intensity of the transmitted part is detected as a function of position and beam parameters. The basic arrangement is sketched here:



Incoherent transmission

In order for such an arrangement to work, the range R of the particles must be larger than the thickness d and the scattering small enough so that characteristic details are not washed out. Actually, in the incoherent case, we can look at the transmitted beam as a particle beam.

In the coherent case, we consider the wave nature of the incident particles (or photons). Scattering from different centers (different atoms or different nuclei, for instance) interferes and typical interference patterns are obtained:



Coherent scattering

In order to obtain interference patterns, the wavelength of the incident radiation must be of the same order of magnitude as the pattern that is being studied. (Actually, this statement is not completely true; at small incident angles, structures with larger dimensions can be observed.)

For photons, the wavelength is connected to the energy by

$$\lambda = hc/E,$$

where h is Planck's quantum and c the velocity of light. For practical calculations, we use

$$\lambda \text{(in A-U)} = 12.34 \,/\, E \text{(in keV)}.$$

For particles with mass m, the wavelength is connected to the momentum p by the de Broglie relation

$$\lambda = h \,/\, 2\pi p:$$

in terms of mass and energy, we get

$$\lambda = h \,/\, (2\pi \sqrt{E^2 + m^2})$$

2. INTERACTIONS AND PARTICLES

Three of the four known interactions are, at least in principle, of interest here: the nuclear (or hadronic) interaction H_h, the electromagnetic interaction H_y, and the weak interaction H_w. In principle, the weak interaction is ideally suited for nondestructive testing; neutrinos pass through light-years of matter. However, except for very special purposes, like looking at the interior of the sun H_w is just too weak. The only interactions to be used then are the hadronic and the electromagnetic ones. The two are completely different in their properties.

The electromagnetic interaction has a long range (Force is proportional to $1/r^2$); its strength is given by e^2. A particle with electromagnetic interaction passing through a medium explores the distribution of electric charges; at low energies, it looks mainly at the electrons in the shell.

The hadronic interaction has a very short range (of the order of fm = 10^{-15} m) and is about a 100 times stronger than H_y. It explores only the nuclei and is not affected by the shell. The particles that are or could be of use in nondestructive testing are shown in the table below.

Particle	Mass		Charge	Interaction hadronic	electromagnetic
Photon	0			No	Yes
Electron	0.51	MeV	+, -	No	Yes
Muon	106	MeV	+, -	No	Yes
Pion	140	MeV	+, -	Yes	Yes
Proton	938	MeV	+	Yes	Yes
Neutron	940	MeV	0	Yes	No
Nuclei	--		+, -	Yes	Yes

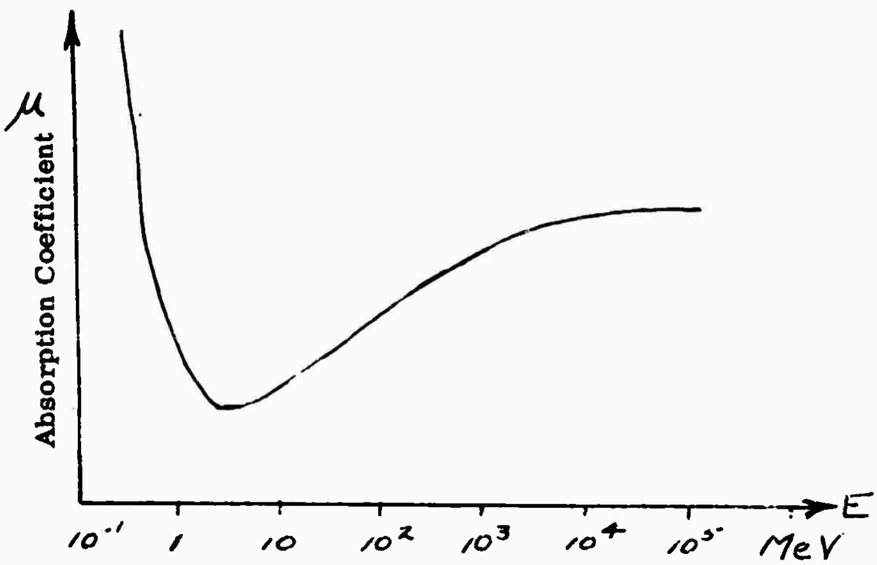
3. PHOTONS

Photons can be used for coherent and incoherent tests; both are very well known. The former lead to X-ray diffraction pictures, the latter to standard "Roentgen" or X-ray photographs.

Photons passing through matter in general are absorbed according to

$$I_x = I_o e^{-\mu x},$$

where I_x is the intensity at depth x and μ is the absorption coefficient. (In Mössbauer effect, this law is modified.) The absorption coefficient depends strongly on the atomic number Z of the material that is traversed. The general behavior, however, is similar for all substances; it is sketched in the next figure. The behavior is of importance for testing. It shows that the absorption coefficient has a minimum and then rises again. In order to look at a thicker piece of material, it is therefore not simply possible to increase the photon energy.

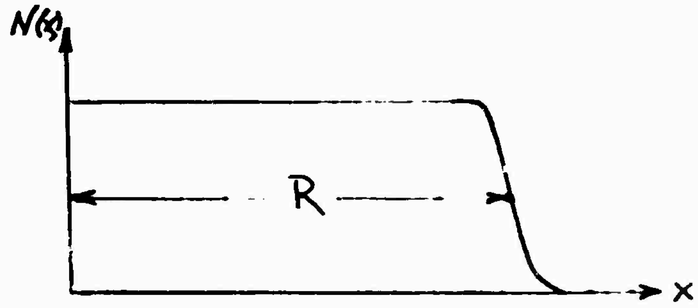


Sketch of the absorption coefficient for the absorption of photons by lead.

4. CHARGED PARTICLES

Heavy and light charged particles behave differently. Consider heavy ones. In the next figure, we plot the number of particles that pass through an absorber as

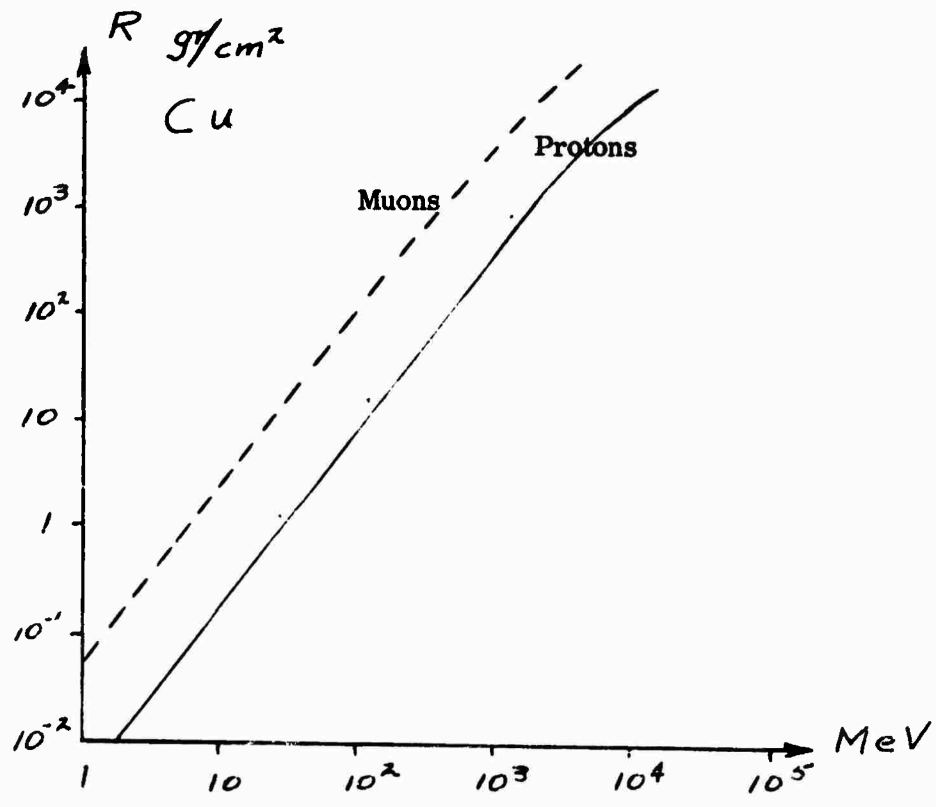
a function of absorber thickness. Essentially all particles with a given energy are absorbed after the same distance, the range R. If the range is known for



Number of particles, in a beam of given energy, that traverse to a distance x.

one particle, it can be found for other particles from the scaling law

$$R/m = f(E/m).$$



Range of protons in copper. The range is given in g/cm^2; to find the range in cm, divide by the density (about 9 g/cm^3).

In the figure above, we sketch the range for protons and muons in copper.

The behavior of electrons is more complicated. Electrons give rise to showers and they cannot be characterized by a range. Neutrons interact only hadronically and their transmission depends only on the nuclear properties of the absorber.

5. SOURCES OF RADIATIONS

For testing purposes, we can distinguish three types of sources:

I. Radioactive sources. These provide small, easily movable sources of electrons, x rays, and alpha particles with energies in the MeV range.

II. Small accelerators. These can range from easily movable x-ray units to Van-de-Graaff's. They can produce x rays, electrons, protons, neutrons, and heavy ions in the energy range up to about 20 MeV. Some of these units are movable, but most units are fixed.

III. Large-scale installations. Nuclear reactors and large accelerators exist only in relatively few places. However, they may perform jobs that cannot be done in any other way. The Los Alamos Meson Factory, for instance, will produce muon beams with energies up to 400 MeV and intensities up to 4×10^8 muons/sec.

6. DETECTORS

Major progress has been made in the development of radiation detectors. I mention only two relatively new types:

Solid state counters detect low-energy gamma rays and charged particles with very good energy resolution. They are small and can probably be used in places where other counters are too bulky.

Spark chambers may be used as a type of "photographic emulsion" for high-energy radiation.

7. SPECIAL EFFECTS

The Mössbauer effect is a special tool that involves gamma rays of energies below about 150 keV. Charged particles, in their passage through matter, may encounter "blocking" or "channeling". All three effects may be useful for nondestructive testing. Finally, Alvarez' study of the pyramids using cosmic rays is a unique example of nondestructive testing.

8. REFERENCES

More details concerning the passage of radiation through matter can be found in the following books:

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13. ABSTRACT Nondestructive evaluation (NDE) must be incorporated into every phase of the design-production-service cycle, including the screening and qualification of materials for new design criteria, in order to design materials to their limits to satisfy the ever-increasing demands of sophisticated military systems. Even in the presence of adequate technology, the key to NDE implementation and maximum hardware reliability is the proper application of suitable specifications. To achieve the necessary reliability at reduced costs, a general management-control specification on the application of NDE to the design-production-service cycles should be prepared and included among the pertinent specifications in DOD contracts. The majority of the technical problem areas facing DOD are well characterized ~~and~~ could be best handled by the proper use of NDE during the development and manufacture of materials and products. Solving NDE these problems requires selecting test parameters, designing tooling, defining acceptance levels and using more than one technique for evaluation. Automatic data processing equipment must be used to attain quantitative capabilities through rapid feedback of data for process control, utilization of all data, comparison with prior data for early detection of trends and to evaluate operational changes. ~~Review~~ of special phenomena did not reveal any new energy form which could have impact on NDE techniques. Among areas recommended for further study were failure mechanism, data processing, lasers, holography, acoustic propagation, and acoustic emission. A greater number of NDE professionals and technicians is needed and could be produced through increased university and other technical training. The establishment of national NDE research and application centers was recommended as was the expansion of the present DOD NDT Information Analysis Center.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Specifications and standards						
Management-control specification						
Education and promotion						
NDE research and application centers						
Information						
NDT information analysis center						
Technical problem areas						
Automatic data processing						
Joining						
Coatings						
Composites						
Graphite and ceramics						
Alloy verification						
Surface cleanliness						
Residual stress						
Fatigue						
Thin materials						
Corrosion and stress corrosion						
Special phenomena						
Lasers and holography						
Acoustic propagation and acoustic emission						

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